LEVEL II

REPORT NUMBER WS: 78 - 2

THE SIXTEENTH UNDERSEA MEDICAL SOCIETY WORKSHOP

MONITORING VITAL SIGNS IN THE DIVER

BETHESDA, MARYLAND

17-18 MARCH 1978

CHAIRMAN AND EDITOR

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Monitoring Vital Signs in the Diver

UNDERSEA MEDICAL SOCIETY, INC.
Workshop

(9) Special rept.

(15) N00014-74-C-0319

(10) Claes E. G./Lundgren

Chairman
and
Editor

(11) 18 Mar 79

(12) 119 p.

(14) WS-78-2

This Workshop was supported by the Office of Naval Research Contract N00014-74-C-0319 with funds provided by the Naval Medical Research and Development Command.

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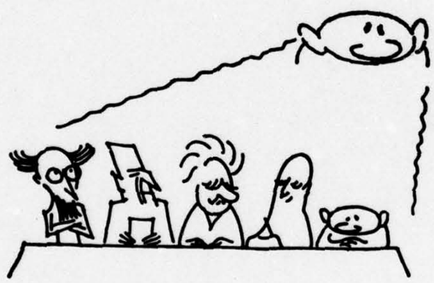
PREFACE

The rough manuscripts and transcripts of the deliberations of this Workshop totalled 200 pages. Though the keynote presentations appear almost in their original form, the discussion sections needed considerable editing; this was all the more necessary because there were several contributions from virtually everyone in this group of 29 impressively knowledgeable and vocal participants.

There were sometimes differences in opinion or emphasis that could not be resolved, and these are presented so that the reader may form his own opinion. For the most part the discussion that focused directly on the topic of a keynote presentation follows that particular presentation. Topics that were not specifically addressed in the keynote presentations may be found in separate sections at the end of the Proceedings.

The Editor



THE ARITHMETIC OF CO-OPERATION

When you're adding up committees
there's a useful rule of thumb:
that talents make a difference,
but follies make a sum.

INTRODUCTION BY THE CHAIRMAN

At the time of this Workshop, five years had passed since a related topic had been addressed by a UMS Workshop* -- five years of advances in operational diving, physiological investigations, and monitoring techniques, and five years of diving accidents. It was therefore felt to be worthwhile to take a new inventory of the methods available for monitoring the diver's well-being and warning of threatened or manifest malfunction in the diver. Our discussions will include both physiological and behavioral parameters that should be considered from two points of view: desirability and practicality. For a certain parameter to be desirable it should be either:

> specific and reflective of a physiological function which, if disturbed, might in itself pose a threat to the diver (i.e., end-tidal CO_2 concentration and hypoventilation) or
>
> nonspecific and indicative of the diver's overall condition (i.e., coherence of speech).

To make the parameter interesting from the practical viewpoint, both techniques for its recording and processing and standards for its interpretation should be within reach. To be applicable in operational diving, the data should lend themselves to processing and interpretation in such a way as to help the non-medical diving supervisor decide how to pace a diver and when to abort a dive.

Although the emphasis at this Workshop was quite rightly placed on ideas that held promise of immediate application, the opportunity to identify possibilities for future development was not overlooked. Because of this emphasis and the practical orientation of the Workshop, electroencephalography was not covered and decompression monitoring was not included because of the necessity to limit the size of the Workshop.

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*Third Undersea Medical Society Workshop: Early Indications of Behavioral and Physiological Dysfunction in Deep Divers. Submarine Development Group 1. San Diego, Cal., 3 - 4 May, 1973.

IS THERE A NEED FOR PHYSIOLOGICAL MONITORING OF THE DIVER, I.

Robert C. Bornmann

I would like to give those here who are not aware of what has happened a historical overview--because there is a clear 10-year history (and it probably goes back even further than that) of the development of monitoring for Navy divers. When Admiral Gallantin was Chief of Naval Materiel, he was asked why the Navy did not use NASA technology to monitor the saturation diver's well-being and safety. A series of conferences was held and the final recommendation listed the following factors as desirable:

1. Voice communications
2. Heart rate (and, if practical, rhythm--an ECG preferred)
3. Inspired partial pressure of oxygen
4. Inspired partial pressure of carbon dioxide
5. Hot water temperature at the inlet of the heated suit
6. Depth

Minutes from one 1969 meeting stated: "...It was unanimous that the single most desirable item for diver's safety was communication to and from the diver. Voice communication <u>to</u> the diver should be clear and reliable; voice communication <u>from</u> the diver should permit monitoring of diver breathing and transmission of voice emergency signals from the diver.... Inclusion of $PICO_2$ requirement in any request for procurement would unacceptably increase the cost of the monitoring system and more importantly delay its introduction into the fleet...." Comment from another meeting recommended the development of a simpler interim system which would provide three elements as a minimum requirement, viz., voice communication, ECG and inspired PO_2. A closed-circuit television monitor would also provide a great deal of additional information on the condition and safety of the diver, and it has been used in some Navy saturation and commercial diving operations. Finally, discussions at the time made a clear distinction between that monitoring necessary for operational dives and the use of monitoring of a host of other factors to provide valuable physiological information during research or developmental diving.

The sensors should be acceptable to the diver. They should not be in his way or constrain him in his job. They should not involve needles under the skin or rectal probes or anything similar. The monitoring system should be easy to put on and take off. It probably should be incorporated into his equipment and be unnoticed by him. Finally, it is preferable to monitor the immediate environment for normal operation of his equipment to give advanced warning of the development of an unsafe situation rather than to monitor him for a late warning of his beginning deterioration.

How has the Navy development program gone since then? The sensors were all available except for an underwater PCO_2 meter. The important questions were all equipment and engineering ones, such as a decision about mode of transmission, whether to use hard-wire umbilical or through-water transmission of signals, and what topside layout best displayed the information obtained. A Navy monitoring system has been developed and was recently considered for procurement.

Several line colleagues are at this meeting with us. I hope that we can take full advantage of their presence for a discussion of how the Diving Officer would use information obtained through a physiological monitoring system: what advantages or disadvantages does he see in its use during a dive. We should also hear the reasons behind the decision not to go ahead with an expensive procurement at this time.

In that regard I would like to point out once again the emphasis placed in 1969 on communications as the essential base for diver monitoring and diver safety. Since the development of the helium unscrambler, good diver communication has been a feature of Navy saturation diving. In other types of diving, and especially in scuba, the development of diver communication is a major challenge.

Dr. Nicogossian is here from NASA. I hope that in his presentation he can not only describe the NASA system of astronaut monitoring but also explain the setting in which it is used. What type of information is presented? How is it presented and to whom? What type of training is necessary to utilize the monitoring information? Also, from his experience as an aerospace medical officer, how does he feel about the importance of monitoring to protect the safety of the astronaut and to ensure completion of NASA mission objectives?

Our divers often dive in small groups. There may or may not be a Medical Officer present. There probably would be a hospital corpsman. I think the topside display should present information that is understandable and usable not only to the doctor or corpsman but also to the Master Diver, the Diving Officer, or any of the other divers. The following questions should be kept in mind during our discussions here: Is the information generated through monitoring superfluous and unnecessary to the diving supervisor? Does the readout present information in a usable form? What purpose does monitoring actually serve? How many false warning signals would be generated? Is the diving medical community prepared to interpret and act on real-time monitoring of the physiological status of divers, and are our training programs adequate to teach Diving Officers, Master Divers and medical assistants how to use and benefit from such monitoring?

Diving is a hazardous occupation and has caused fatalities. I can think of one or two instances where a monitoring system of this type should have warned of a serious problem before the fatality

occurred -- and more importantly given that warning in time to take steps to avert the fatality. If such incidents were not uncommon, they would be a strong argument for monitoring no matter what the cost. Use of a monitoring record to help reconstruct what might have gone wrong in a fatality is another but lesser consideration.

I am going to be followed in just a few seconds by Dr. Elliott. I wonder whether there are any incidents in the North Sea that he is aware of, and can talk about, that would indicate a similar situation. Coming over here this morning, I wondered whether an analysis could be done of diving deaths reported in the Naval Safety Center, to see whether a monitoring system might have prevented what did ensue.

Discussion

The Chairman noted that Dr. Bornmann had formulated several questions of general application, such as 1) how many false warning signals would be generated by whatever system we can think of?; 2) are we of the medical community prepared to interpret and act on real-time monitoring?; and 3) is our training program adequate for teaching Diving Officers to do the interpretations? The Chairman then suggested that these questions probably could be best answered later in the Workshop. Comments were invited for Dr. Bornmann's specifically Navy-oriented question--what was the reason for deciding not to use the monitoring system that had been developed after 1969? Also, it was suggested that the Workshop participants should be apprised of the proposed Navy monitoring system's capabilities.

Dr. Spaur summarized that the system had a device for PCO_2 measurement to be attached to the breathing hose of the diver's breathing apparatus. It was basically an infrared analyzer that required temperature control, depth control and heating of the mirror elements. An oxygen sensor that was polarographic and quite dependable, although somewhat expensive, was also part of the system. Furthermore, an ECG recording from standard chest leads was included. Respiratory rate was taken from a fast thermostat near the mouth. It also recorded diving suit water temperature. In addition, it provided for communication with the diver. Signals were fed through 17 wires through a multiplexer containing electronics and which could not be run in air because it heated up too much. The presentation of data on water temperature, inspired gas temperature, as well as respiratory rate, ECG, and oxygen pressure had high- and low-level alarms.

Cdr. Duff explained that the reasons the Navy did not introduce this system for routine use were: 1) cost; 2) extreme difficulty in maintaining calibration of the equipment; 3) the expertise required to keep the equipment working; and 4) there was no good high usage factor for this expensive piece of equipment (cost was given by somebody as between \$30,000 - \$40,000 per unit). Dr. Bornmann added that this decision had been a team-Navy decision and that he fully agreed with it.

IS THERE A NEED FOR PHYSIOLOGICAL MONITORING OF THE DIVER, II

David H. Elliott

The monitoring of a diver may be undertaken for several different reasons, of which the most obvious and probably the most important is safety. The diver may also be monitored to ensure his maximum working efficiency at depth and it may be of clinical value in the diagnosis and management of diving-related illnesses, especially those of decompression, to monitor the diver. This Workshop is confined to consideration of the physiological monitoring, wet or dry, relevant to the performance and safety of the diver in the water.

In the last 5 to 6 years there have been nearly 40 deaths in the North Sea.* Is it possible that on-line monitoring might have anticipated unconsciousness in any of these divers? The UK Department of Energy has already made it known that it is considering the need to make it mandatory to monitor respiration. Informally it has been agreed that this requirement would be met by recording the sound of breathing behind the voice, provided that each diver is on a separate channel. However, a closer study of the fatalities in the North Sea does not necessarily support the idea that monitoring of the diver would do much to increase safety and reduce the accident rate. In several cases the evidence is insufficient and in some there is court action pending which prevents public discussion. In general, however, analysis suggests that the majority of these fatalities were a consequence of poor training, a *mechanical fault*, a *procedural* error, or some combination of these factors. Physiological monitoring might not have predicted the outcome. Nevertheless, the possibility that in the North Sea or elsewhere some simple monitoring procedure might prevent a death is sufficient justification for our urgent evaluation and reappraisal of monitoring techniques.

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*Editor's note: In connection with presenting this paper, Dr. Elliott mentioned that in the few months that had passed since he wrote the manuscript there had been four more deaths among North Sea divers. He added that the vast majority of diving accidents were due to equipment failure and procedural error--the latter involving poor training, poor judgment, improper dive planning, and insufficient supervision. He said that he was not sure that monitoring the diver would have made much difference in the outcome of these accidents, with perhaps one exception. Dr. Elliott went on to suggest that the Workshop should address the provocative hypothesis "monitoring contributes nothing to diving safety." He also expressed hope that this hypothesis would be disproven during the Workshop.

Before demanding that the diver in the water be monitored, some basic questions need to be answered. What physiological or pathological event is to be monitored and why? By what technique is this to be done? Who is to interpret the results and take appropriate corrective action?

Some simple methods of monitoring have been used for years. The untethered diver needs to know at least his depth, the accumulated duration of his dive, and the remaining pressure in his gas bottles, but physiological monitoring is confined to a subjective assessment of his own condition. With the addition of a life-line or an air-hose, the tender is able to monitor, in the simplest possible sense, the continued vitality of his diver by means of intermittent rope signals. The addition of voice communication from the diver, through a helium unscrambler if appropriate, and of television surveillance brings us up-to-date with the extent of monitoring available to many diving supervisors. How much more is necessary?

At the previous UMS Workshop in 1973, it was concluded that heart rate, respiration and a number of measures of neurological function were parameters of importance to operational deep diving, but this Workshop is not confined to deep diving. We must also address the other problems of operational diving. In this context it is relevant that the majority of recent fatalities in the North Sea have not occurred at great depths but have been on compressed-air dives.

The compressed-air diver does not need to know much more than depth, time, and the state of his gas supply. Certainly the diver is well aware of his own respiratory rate and should have been trained not to exert himself excessively. This implies that the requirement for respiratory rate to be monitored topside on the voice channel may not make a significant contribution to diving safety. Heart rate is not so easy to quantify subjectively, and there may be some merit in providing the diver with a device which would enable him to self-pace his rate of physical exertion. But self-monitoring is not always appropriate. The assessment of perceptual narrowing and attentiveness almost anticipates an answer to the question "monitored by whom?" In complex designs of breathing apparatus, monitoring of oxygen tension may be an example of a readout that should be available to all members of the diving team.

Is it perhaps preferable to monitor the equipment rather than the man? In deep diving the monitoring of inlet temperature to a hot water suit is more practical than monitoring the diver's body temperature. But cold is a contributory factor in many underwater accidents. Thus there may be a case for monitoring the temperature of divers who are not provided with supplementary heat. More practically, it might be better to suggest a more widespread provision of adequate insulation and heating for compressed-air divers.

Monitoring of performance should attempt to guarantee that the diver has, at all times, the ability to get himself out of a threatening situation.

Summary

Thus, we need to know:

What physiological parameters can be monitored to provide on-line information relevant to the continuing safety of the dive? Need such monitoring be continuous or can it be intermittent?

Is the technique relatively easy? Is it accurate? What is the response time? What is the range of normal and how is the threshold of abnormality defined?

Of the monitored functions, which ones need to be fed back to the diver for remedial action and which need to be interpreted by the tender or supervisor?

To what extent would it be practical to record monitored variables for later retrospective analysis in case of some accident?

Discussion

After Dr. Elliott's presentation, several discussants observed that whatever is going to be monitored has to be interpreted in a simplistic and clearcut way. On the other hand, it was pointed out that the reason we do not know exactly what the most useful parameters to monitor are may be that too little monitoring of any kind has been done in the diver.

Upon mention by Dr. Elliott that the UK Department of Energy contemplated making the monitoring of respiration mandatory, Dr. Barnard commented that one of the more prominent advocates of such a regulation is a man experienced in practical diving, who presumably does not know the depth of our ignorance with regard to making sensible use of physiological monitoring.

Dr. Braithwaite took note of the suggestion by several discussants that proper supervision of the diver is a very important safety factor. He observed that monitoring and recording communications is probably the best way to monitor supervision in addition to offering a good clue as to the cause of an accident, should one happen. It was also pointed out that the case is similar to that of aircraft monitoring: even after a fatal accident, a continuous record of the events may contribute to the safety of future dives.

It was agreed that there were two important questions to consider at this Workshop: "What predictive package would be of value?" and "What retrospective analysis would be of value?"

HEART RATE MEASUREMENT AND INTERPRETATION

Kenneth N. Ackles and Geoffrey R. Wright

The electrocardiogram is probably the easiest and most basic physiological parameter that can be measured in an operational dive. However, at the present time, it is not used routinely due to uncertainties of interpretation in the field. Several problem areas must be considered before usable information can be obtained. This includes: type and position of electrodes; placement of pre-amplifiers; signal interface between diver and surface control; and the relative merits of analog signals versus digital presentation.

Type and Position of Electrodes

Both stick-on and subcutaneous electrodes can be used to pick up the electrical potentials generated by the cardiac cycle. Disposable stick-on electrodes are readily accepted by divers for heart rate monitoring during most operational dives. Provided that a few precautions are taken, these stick-on electrodes are suitable for use in both wet and dry suits. First, care must be taken with any pre-gelled electrodes to ensure that the paste has not dried out; we routinely add extra electrode gel. To reduce water intrusion, the center of the electrode and the snap-on lead can be coated in grease and the resulting junction can be coated in colloidion. Surgical tape should be used to cover the electrode-lead junction. Though diving suits and undergarments minimize electrode displacement, it is still advisable to cover the electrode with extra tape; a small loop in the electrode lead placed under the tape ensures that any quick movement does not strain the lead-junction interface. This additional covering is beneficial in both wet and dry suits; in the former it provides an extra water repellant layer, while in the latter it helps maintain electrode contact if the diver is sweating slightly. For long-term saturation dives, serious consideration should be given to subcutaneous electrodes. These electrodes, though causing minor discomfort on insertion, can remain in position for several weeks without restricting the diver's activities, and they provide excellent artifact-free recordings.

The position of the ECG electrodes should be selected to provide a maximum QRS complex with minimal interference from muscle artifact. This means that electrodes must be positioned over bone with minimal muscle overlay. One possible lead placement is: reference electrode on the manubrium sterni (CM5), the exploring electrode on the anterior axillary line of the left 5th intercostal space, and the neutral lead on the back of the neck (Blackburn et al. 1967), or alternately on the sternal area. We have found it advantageous to use three electrodes rather than two so as to use a common-mode rejection pre-amplifier.

Such a system creates an input differential through a high common-mode rejection ratio; that is, in-phase signals are cancelled while out-of-phase signals (the ECG) are amplified. This significantly reduces electrical artifacts due to 60-Hz noise or other electrical interference.

Placement of Pre-Amplifiers

Since the electrical potentials generated by the cardiac cycle are low-voltage signals (usually less than 10mV), some form of signal amplification is required. Since high background interference under water is unlikely, it is possible to transmit this low-level signal, which is received and then amplified. However, the more conventional system, used to eliminate background noise, is to amplify the signal before transmission over a low impedance line. This is ideal in the "hard-wired" situation, where 1-to-2 volt amplification is sufficient to transmit a signal from the diver to the surface, diving bell, or submersible.

Signal Interface Between Diver and Surface Control

For most operational and commercial dives, the diver is directly attached to the surface, diving bell, or submersible by an umbilical. Since a few electrical leads will not add any significant weight to the umbilical system, the most suitable interface is the "hard-wired" or direct method. In the past, this direct communication has been accomplished by electrical transmission. A more recent development is the introduction of fiberoptic communication systems that use light waves to carry information through hair-thin threads of glass. Though this system permits a greater number of independent channels to be carried for a given size of umbilical, this does not appear to be an advantage over electrical transmission unless a greater number of physiological parameters are monitored during a deep dive controlled from the surface. Ultrasound has also been used for data linkage, but the pre-amplification voltages are generally too high to allow direct transmission from the diver to the surface. However, ultrasound can be used safely in conjunction with a submersible where low-voltage signals can be received from the diver, then encoded onto the ultrasound voice communication system of the submersible for transmission to the surface support ship. For free swimming divers, telemetry can be used successfully. However, in our opinion, the use of batteries in excess of 10 volts should be avoided. Thus, the receiving antennae should be in close proximity to the diver.

If at all possible, the use of batteries on the diver should be avoided. Because of problems of seawater leakage and remembering to change or charge batteries, a system for use in operational diving should receive power from the umbilical.

Analog ECG Signal vs. Digital Rate

Another consideration is the relative merits of transmitting analog ECG signals or digital rate information. Generally, the easier it is to obtain the signal, the higher the degree of interpretation required. For example, the raw analog ECG signal is relatively easy to obtain but requires a high degree of medical expertise for successful interpretation. However, conversion of the raw ECG signal to rate information will allow monitoring by less technically qualified individuals. Considering the greater complexity of the electronic package carried by the diver and the possibility that a continuous record of the basic ECG signal could be required after the dive, a strong case can be made for transmitting an analog ECG signal to the submersible or surface support ship. Then, depending upon the information required and the desired level of sophistication, the analog signal can be processed further.

Additional Processing

Although analog ECG tracings can be converted manually to heart rate information, efficiency at the dive site dictates automation of this process. This transformation can be accomplished readily by means of a cardiotachometer. Basically, a cardiotachometer consists of electronic circuitry to detect QRS complexes in the ECG and, either by analog or digital methods, to measure the time interval between successive beats. This interbeat interval (IBI) is then converted into an instantaneous heart rate. For digital display of this instantaneous heart rate, it is usually desirable to provide smoothing or averaging circuits to prevent readout flicker.

Once the ECG has been converted to a digital readout, upper and lower heart rate limiting alarms should be added. However, one important difficulty with alarm systems is the problem of false alarms. False alarms can be minimized by careful selection of the type and position of the ECG electrodes and by selective filtering. In addition, it is advisable that the alarm circuitry require that the heart rate remain outside of the set limits for at least five consecutive beats.

The low alarm limit is easily set; only a resting (or sleeping?) diver would have a heart rate below 50 beats per minute. Setting an upper limit tends to be more controversial since it requires agreement on the effects of various stressors on the diver's heart rate. The stressors that come to mind immediately are heat stress, work stress, and psychological stress. It is our opinion that the diver's heart rate should not exceed 160 beats per minute for more than three minutes at a time. This limit is based on a consideration of the above stressors and applies to pre-dive monitoring as well. For example, Lemaire and Murphy (1977) observed heart rates in excess of 160 beats per minute during dressing due, in part, to elevated core temperatures.

Although monitoring heart rate should not replace the direct measurement of core temperature, heart rate does provide a useful index of heat stress since it reflects the additional physiological demands placed on the body.

The monitoring of heart rate appears to provide the most immediate benefits for the diver in the area of work stress. The upper alarm limit, then, is of particular importance if a top-side controller is to prevent a working diver from over-exertion. The principles are well established for industrial work situations and have recently been applied to the diver (Bell and Wright 1977). Basically, the higher the individual's heart rate, the shorter the allowable work cycle. For example, the total daily time limit for a task requiring 75% of an individual's maximum aerobic power is approximately 27 minutes, while the time limit for a task requiring 60% of the individual's maximum is 79 minutes. With an average maximum heart rate of between 190 to 200 beats per minute for divers ranging in age from 20 to 30 years, a diver will reach 75% of his maximum aerobic power at a heart rate of 160 beats per minute. Thus a diver could approach our arbitrary 160 beat per minute limit nine times within the dive and still be just within a "safety envelope." However, information on heart rate trends would only be evident in the operational setting if a pen recorder provided a continuous plot of the data. The application of automated analysis systems to this area could prove extremely useful. The displayed output could take the form of a histogram with heart rate plotted against cumulative time at that rate. Then, as in the example, a simple rule could be applied to the diver to determine if he has exceeded an accepted work stress level.

The sequential digitizing and subsequent storage of heart rate information on magnetic tape would permit analysis of heart rate variability. This could prove useful in assessing the degree of psychological stress imposed by a given situation. Although such techniques are still in the early stages of development, advances are being made. For example, analysis of a DCIEM dive to 7 ATA has shown that the combination of the successive difference mean square as the measure of heart rate variability and inter-beat intervals as the scale of measurement for heart rate was both the most sensitive and most appropriate statistical technique for assessing changes in heart rate variability at rest while breathing either air, oxy-helium, or oxy-argon. Although further evaluations of this measure are planned, the approach looks promising because it was able to differentiate between the varying degrees of narcosis, that is, oxy-helium, then air, and then oxy-argon. Future developments would include a real-time analysis, again with diver safety being the prime consideration.

Conclusion

Although several problem areas must be considered to ensure that usable heart rate information is obtained, it is evident that none of the technical problems are insurmountable. Indeed, it appears that the greatest obstacle is not technical but educational, for there is reluctance on the part of divers to make physiological monitoring a regular part of their dive protocol.

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Discussion

Dr. Ackles' presentation stirred a lively discussion of the feasibility and usefulness of ECG monitoring. With regard to the technical aspects, some discussants felt that a full-blown analog ECG was too complicated for the real-world diving situation and that inconvenience and risk of infection would certainly rule out the use of subcutaneous electrodes. However, there was agreement that recording heart rate was more feasible either by means of a cardiotachograph converting ECG signals from a simple two-lead recording (or three-lead for redundancy) or else from some type of pulse registration. Dr. Fagraeus referred to experience with ECG monitoring both in divers and in the operating theater that had made him suspicious of the practicality of ECG monitoring in open-sea conditions. He suggested the alternative of employing the precordial ultrasound Doppler probe, which could then perhaps also be used for detection of gas emboli during decompression.

There was some dissension as to how useful cut-off values for heart rate would be. However, strong support for the approach of Drs. Ackles and Wright was expressed by Dr. Egstrom. He mentioned that in routine monitoring of heart rate of working divers, he and his collaborators had found that there was a definite tendency toward self-paced work, the diver tending to restrict his effort to confine heart rate within a range of 110-150 beats/min. Whenever the frequency jumped above that range, simultaneous T.V. monitoring revealed that something unusual was occurring.

Dr. Bennett also spoke in favor of using heart rate monitoring as a means of preventing the diver from over-exerting himself, suggesting that the limit that the diver should stay under probably could be set at about 160 beats/min. The point was made that heart rate may become more diagnostically valuable in combination with other physiological parameters, but the degree of sophistication required for integrated interpretation would far exceed what is available on a diving platform unless this integration could be automated and presented in a form that is easy to read and act on.

MONITORING THE DIVER'S VENTILATORY SITUATION

Edward D. Thalmann

In individuals in good physical condition, dry exercise at 1 ATA is limited by the ability of the cardiovascular system to deliver oxygen to exercising muscle as well as the aerobic capacity of the muscle. That the ventilatory system performs its tasks easily up to maximum oxygen consumption is evidenced by the very small amount which arterial PO_2 drops and the fact that arterial PCO_2 does not increase but drops with increasing exercise (3).

For individuals exercising at increased ambient pressure, blood PO_2 is maintained if the inspired PO_2 is sufficient, but CO_2 retention is a consistent finding at sufficiently high gas densities (13,21,22, 26,27,29). This CO_2 retention is mainly a function of a depressed ventilatory response to exercise caused by the increased gas density (12,18,20). Increasing the external breathing resistance will further depress ventilation and thereby exacerbate the CO_2 retention (5,11, 12,30). Even with end-expired CO_2 levels greater than 60 mmHg, the subjects of Linnarsson and Fagraeus (23) were able to perform maximum oxygen consumptions in the dry at densities of 6 gm/liter, although the dyspnea during these levels of exertion is more severe than at 1 ATA.

The effects of immersion have been studied at rest and include increases in cardiac output (17), decreases in FRC and RV (2,8), diffusional changes (4), increased pulmonary air trapping (9,10), changes in lung mechanics (1,19,25), and changes in ventilation-perfusion distribution (2,24). Unfortunately, very little is known about the effects of immersion on the exercising immersed subject. However, that the effects of immersion on exercising divers are important is supported by the work of Spaur et al. (29), who reported severe work-limiting dyspnea in completely submerged subjects exercising in the sitting position on a bicycle ergometer at 1600 fsw while breathing helium-oxygen with an inspired PO_2 of 0.5 ATA. The oxygen consumptions during these work loads (2.0 liter/min) were less than in the dry study of Linnarsson and Fagraeus (23) cited above, and arterial blood samples showed adequate blood oxygen partial pressure and no hypercapnia. The mechanisms by which immersion influenced the dyspnea observed in this study were not evident from the data.

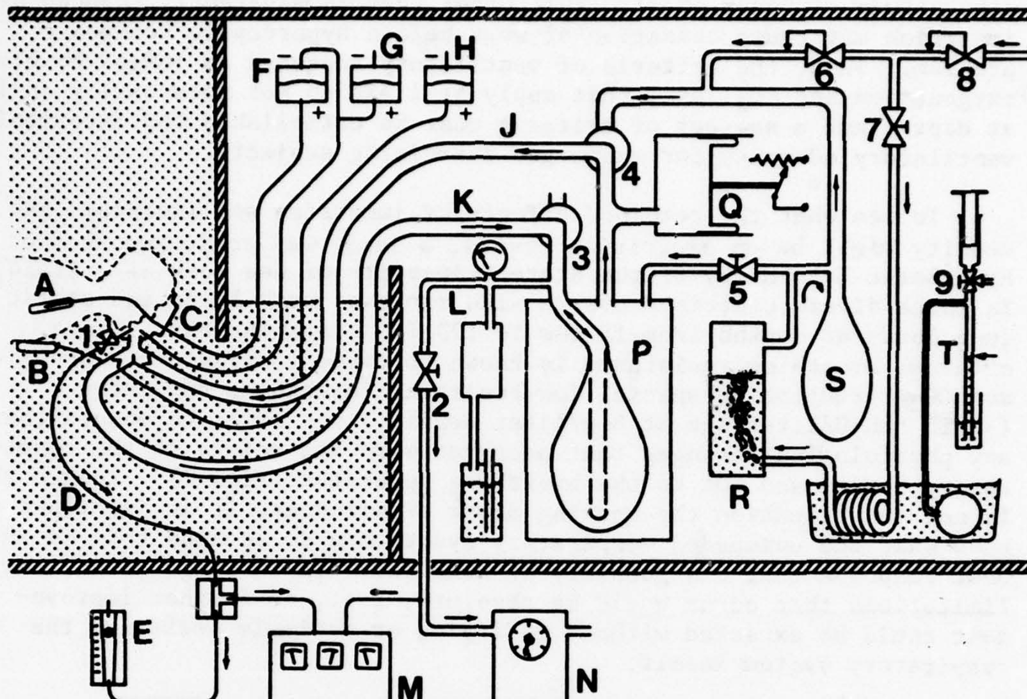
Since the dominant finding during exercise at depth has been CO_2 retention, attention has focused on this parameter to give indications of ventilatory adequacy. According to the criteria that would be applicable at 1 ATA, ventilation at depth is inadequate, since there is CO_2 retention but hypercapnia *per se* seems to be tolerable up to fairly high levels (6,20,23,28). Also, from the previously

cited study of Spaur et al. (29), other factors apparently induced by immersion may cause cessation of work before hypercapnia becomes a problem. Thus, the criteria of ventilatory adequacy as judged by blood oxygenation and CO_2 level that apply at 1 ATA do not necessarily apply at depth, and a new set of criteria must be established for determining ventilatory adequacy for submerged exercising subjects.

To see what the combined effects of immersion and increased gas density might be on exercising divers, a study was conducted at the Hyperbaric Laboratory of the State University of New York at Buffalo in which divers exercised over a wide range of work loads and static lung loads at depths from 15 fsw to 190 fsw breathing air. Since external breathing resistance is known to cause ventilatory depression and CO_2 retention, a special low-resistance breathing apparatus (<1.25 cmH_2O/liter/sec at 8 g/liter density) was built to ensure that any physiological changes that occurred were due solely to the respiratory system and not to the breathing apparatus (Fig. 1). Though this is not the situation the working diver experiences, it is important to know what the unimpeded respiratory system can do because this is the best response that can possibly be obtained. In this situation, any limitations that occur would be absolute, i.e., no further improvement could be expected without modifying or actively assisting the respiratory system itself.

The variables in this study were depth (gas density), work load, and static lung load; all the experiments were done in the prone position. Both maximal and submaximal work loads were done. The static lung load was defined as the difference between the pressure at the mouth and the hydrostatic pressure at the mid-thoracic line (Fig. 2). The subjects were intensely monitored; the parameters monitored and those calculated from the data are shown in Table 1. Figure 3 shows the ventilation, heart rate, and end-tidal PCO_2 response to increasing oxygen consumption at 15 fsw both wet and dry and at 190 fsw wet. Minute ventilation showed the best correlation with oxygen consumption over the range of submaximal exercise. End-tidal CO_2 showed the characteristic decrease with increasing exercise at 15 fsw even up to maximum exertion, while at 190 fsw there was considerable hypercapnia. The heart rate response to exercise was approximately linear but had such a large variability that it correlated very poorly with exercise level.

During the Buffalo study, dyspnea was never work-limiting except during maximum exercise at 190 fsw. This dyspnea was characterized by 1-2 minutes of uncontrollable hyperpnea and inspiratory and expiratory stridor. No rales or ronchi were heard on ausculation of the chest. The dyspnea, though apparent during exercise, seemed to increase in intensity during the first minute after cessation of exercise. This dyspnea prevented two of the three subjects from completing the maximum work loads at relatively negative static lung



LEGENDS FOR FIGURES

Fig. 1. Low-resistance breathing apparatus. With diver on system valves 3 and 4 are turned so that he is inhaling from barrel of Bag-In-A-Box (P) and exhaling into bag. Spirometer (Q) provides counter lung volume, giving a breath-by-breath spirogram. Breath-by-breath gas samples are taken from mask and routed outside chamber through sample line (D) to mass spectrometer (M). Sample flow is regulated by metering valve (1) and monitored by flowmeter (E). With diver off system, valves 3 and 4 are turned so he is inhaling from bag (S) and exhaling into chamber. Bag (S) is kept full of humidified air by metering valve (7) and humidifier (R). Demand regulator (6) would provide diver with emergency breathing air should bag (S) collapse. To empty bag, diver is turned off system and valve (5) is opened. Metering valve (2) is throttled to provide dry gas meter with proper flow rate, and exhausted gas composition is measured with mass spectrometer (M). As bag empties, fresh humidified gas fills barrel through humidifier (R) and valve (5). Bag overboard emptying system (L) contains a vacuum gauge that will register a vacuum when bag is completely empty, signalling operator to shut valve (2). Water trap limits vacuum to 6" of water, preventing damage to bag should valve (2) not be shut in time. Chamber depth is regulated precisely by setting water level in manometer (T) to a mark when desired depth is reached. Stopcock (9) is turned, sealing system, and as long as water column level remains unchanged, chamber depth is constant. Water column is visible to chamber operator through a port.

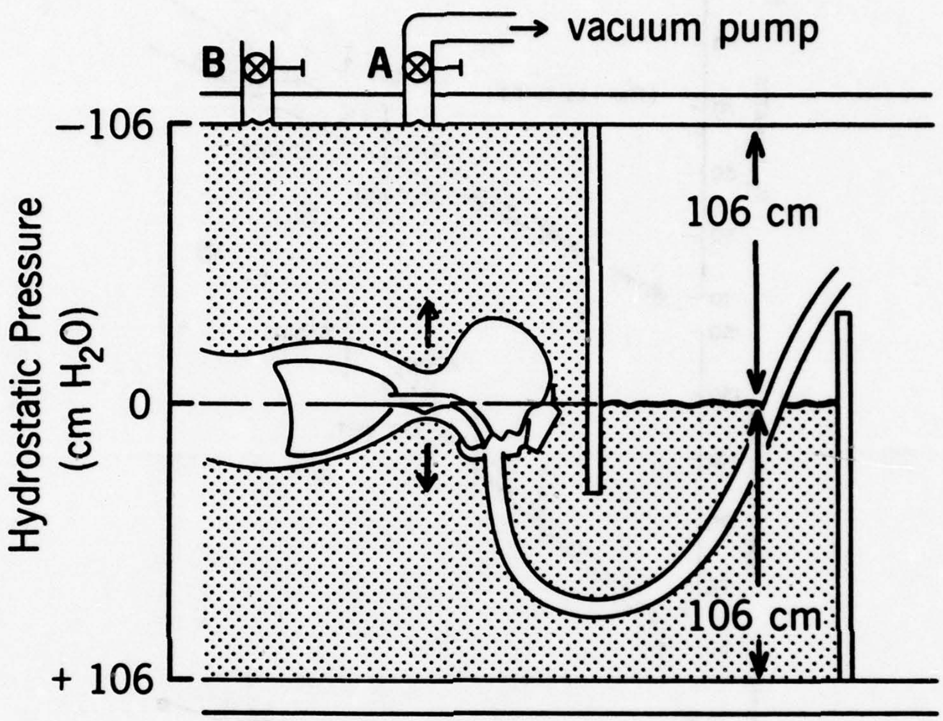


Fig. 2. Static lung loading. By positioning subject at different levels relative to interface, different static loads are imposed on his lungs. With the water level unchanged, mouth pressure relative to hydrostatic pressure increases (+ loading) as subject is raised above interface. As subject is lowered, mouth pressure relative to hydrostatic pressure decreases (− loading).

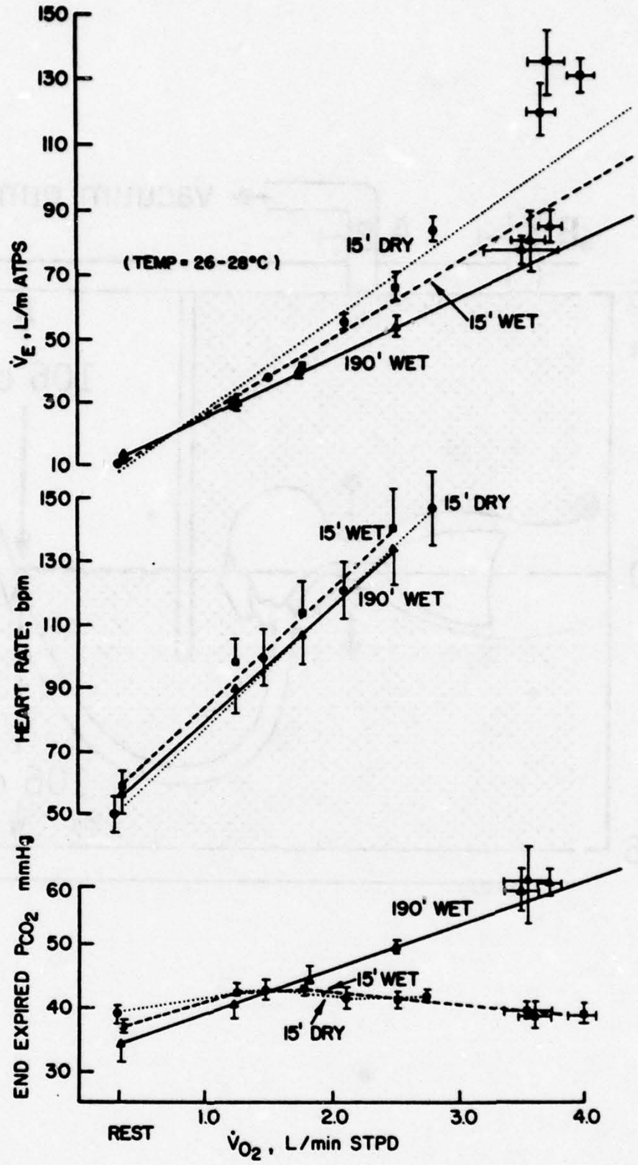


Fig. 3. Minute ventilation, heart rate, and end-expired PCO_2. Response to exercise. All submaximal values are means for all 3 subjects at all static lung loads. Maximum oxygen consumption points have standard error bars for both x and y values and are means for each of 3 subjects at all 3 static lung loads.

Table 1

Ventilatory parameters

Measured	Calculated
Minute ventilation (liter/min, BTPS)	Oxygen consumption
Mixed-expired PO_2	CO_2 production
Mixed-expired PCO_2	Respiratory quotient
Heart rates	Alveolar ventilation
Breathing frequency	Physiologic dead space
Vital capacity	
Expiratory reserve volume	
Tidal volume	
Respiratory flow rates	
Esophageal pressure	
Mouth pressure	
Hydrostatic pressure at the mid-thoracic line	
End-tidal PO_2	
End-tidal PCO_2	

loads. The subject's ability to complete a given work load was unrelated to his MVV, and in many cases the subject's MVV was less than his minute ventilation during maximum exercise.

The dyspnea experienced by these divers during VO_{2max} work loads at 190 fsw was more than a discomfort: it would have posed a serious danger to divers in the open sea because of the intense period of uncontrollable hyperpnea after cessation of exercise. During this post-work period, any situation that would have required the diver to hold his breath, i.e., losing the breathing apparatus mouthpiece, would have been disastrous.

The results of the work at Buffalo demonstrate several phenomena. The first and most important is that at depth the respiratory system itself becomes limiting, even when external breathing resistance is kept to a minimum. Second, hypercapnia occurs on air at sufficient depth, and this hypercapnia does not per se seem to limit exercise level. Third, divers are capable of doing exercise at oxygen consumption levels of 2.5 liters/min at substantially increased gas densities (air at 190 fsw has about the same density as 1600 fsw on $He-O_2$) without difficulty over a wide range of static lung loads. Finally, divers are quite capable of exercising to levels at which post-exercise dyspnea and hyperpnea pose a significant safety hazard. One unfortunate part of the Buffalo study was that despite intensive ventilatory monitoring, no single parameter was measured that predicted the onset of the severe work-limiting dyspnea observed at

190 fsw. It is also interesting that during the Buffalo study, the divers were able to work at higher oxygen consumptions at 190 fsw on air without dyspnea than could the divers in the study of Spaur et al. (29) in which divers exercised at 1600 fsw on helium, although the two studies were done at similar gas densities (8 gm/liter). The reason for this may have been the negative static lung load the subjects in the Spaur study were subjected to by the breathing apparatus or some unknown effect of the greater hydrostatic pressure at 1600 fsw or a combination of both. Also, one cannot discount the possibility that the 0.4 ATA O_2 breathed during the 1600 fsw dive may in itself induce physiologic restrictions.

The question now becomes: how applicable are the results of the Buffalo study to working dives? Though the air breathing medium subjected the divers to hyperoxia, evidence suggests that this can account for only a portion of the observed effects (7,14,15,16). The Buffalo study provides a firm basis for describing the interactions of immersion and gas density effects on exercising divers and would be applicable to real diving situations. There is no question that further work is needed to define better the effects of external breathing resistance, various inspired oxygen tensions, and position on the diver. However, at this point it is probably safe to say that formulating a set of objective criteria for assessing ventilatory inadequacy in the exercising diver at depth is not going to be easy. It appears that the influences of ventilation rate, breathing resistance, static lung load and CO_2 production all combine to produce a situation in which severe dyspnea may be a problem for some individuals. At present, it seems that as long as severe dyspnea is avoided, divers can work comfortably, and the task then becomes monitoring enough parameters so that these areas are avoided. The experience at Buffalo shows that the diver himself is a poor monitor of his ventilatory situation and can get into trouble given sufficient motivation (coercion by the investigator at Buffalo, emergency situations in the ocean); being able to monitor the diver's ventilatory situation from the surface would therefore be valuable. Certainly, the external breathing resistance of the breathing apparatus and the static load on the diver's lungs should be optimized to provide minimum respiratory impairment. The Buffalo study suggests that a ± 10 cmH_2O static lung load is beneficial. During exercise, both the CO_2 production and oxygen consumption are linearly related to the minute ventilation at a given gas density and oxygen level, and therefore knowing the $\dot{V}E$ would provide a very reasonable estimate of the $\dot{V}O_2$ and $\dot{V}CO_2$. It would also be desirable to monitor end-expired PCO_2, but even this could probably be estimated from minute ventilation, given gas density and breathing rig resistance values. Thus, knowing what the breathing characteristics of the breathing apparatus are and monitoring minute ventilation would probably give an adequate picture of the diver's ventilatory situation for a given breathing medium. As additional data become available, it may be possible to develop a set of criteria that will allow surface support personnel to caution the

diver when he is getting into a dyspnea-provoking situation, thus avoiding a potentially dangerous situation. The amount of additional work needed to firmly establish areas of ventilatory adequacy and inadequacy is presently unknown, but it appears that the benefits to be derived would make the pursuit worthwhile.

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Discussion

In the discussion after Dr. Thalmann's presentation, it was noted that the end-tidal carbon dioxide values measured during exercise increased with the severity of the exercise. Someone asked whether one convenient way of keeping the diver out of dyspnea would be simply to monitor end-tidal carbon dioxide and pace the diver to stay below a given level. Dr. Thalmann explained, however, that the carbon dioxide level was absolutely unrelated to whether or not the subject became dyspneic. By contrast, there seemed to be a much better correlation between minute ventilation (being high) and dyspnea, and the differences in ventilation among the subjects were very small. He therefore concluded that minute ventilation is a promising possibility for diver-monitoring, emphasizing that ventilation is subject to much less variation among individuals for any given exertion level than is heart rate. However, he also noted that ventilation would be influenced by depth (gas density) and by the diver's breathing apparatus to the extent that it imposes breathing resistance.

It was recognized that it is still technically difficult to record minute ventilation, whereas breathing frequency would be easier to obtain, for instance over the diver's microphone or by temperature recording in the mask/mouthpiece. Breathing frequency would, however, only yield limited quantitative information about lung ventilation, but it was thought to have some value as an indication that the diver is breathing, i.e., is alive.

Dr. Webb said that if one were interested in the diver's metabolic activity, there are recently developed methods for measuring it as oxygen consumption. He added that this would be preferable to trying to conclude something about metabolism from ventilation measurements. To this Dr. Thalmann answered that he could see only one value in direct monitoring of oxygen consumption: to relate to some set limit that should not be exceeded should one want to set such a limit. On the other hand, information about ventilation would be of value in itself (in addition to being a good indicator of metabolic activity), Dr. Thalmann asserted. In his experience, high ventilation tends to create problems for the diver as it is coupled with dense breathing gas and flow resistive problems in the airways of the lungs.

It was suggested that recording the pressure in the breathing gas cylinders might be one method of monitoring ventilation; however, doubts were expressed concerning the accuracy of this method. The fact that there may be individual variations in adjusting to the stresses of underwater exertion prompted a suggestion: divers should be screened to have their physiological profiles identified so that any deviation in parameters monitored during actual diving could be evaluated with greater certainty.

BODY TEMPERATURE MONITORING

Paul Webb

Divers get cold. The exceptions to this rule are probably remembered with pleasure. Being cold means two things. First, hands and feet get cold, and second, the body itself loses heat, with eventual lowering of deep body temperature. The purpose of body temperature monitoring is to keep track of body heat loss.

Cold hands and feet are best recognized by the diver himself. His sense of discomfort, pain, or numbness, and the diminishing usefulness of his hands and feet, are much better recognized by the individual than by skin temperature sensors. This being the case, there seems no point in monitoring for cold extremities.

On the other hand, loss of body heat is something that is extremely difficult for a person to recognize. A man is a poor judge of his general thermal state. As body heat is lost, the situation is one of approaching hypothermia.

Recognizing hypothermia in its early stages is the real problem in diving. Deep hypothermia, meaning a rectal temperature of 35°C and lower, is a situation to be entirely avoided. In this stage, a diver soon becomes helpless. Deep hypothermia is very likely the cause of some otherwise unexplained diving accidents.

Early hypothermia has an insidious onset. It is sneaky and dangerous. The diver himself may not recognize it at all. The danger comes because in early hypothermia higher order mental functions are affected, in ways which are not yet quantified. Errors in judgment, repetitive behavior, and other inappropriate responses are the important, if ill-defined, features of early hypothermia.

There is, of course, the opposite condition, that of hyperthermia. We now know because of one accident in the North Sea that hyperthermia in a hyperbaric chamber can be lethal in a very short time.

The speed of heat loss or heat gain in a hyperbaric environment is impressive. We are accustomed to thinking of a poorly insulated man in cold water losing heat rather quickly. We are not yet quite accustomed to realizing how fast heat loss and heat gain occur in dry hyperbaric conditions when the temperature is only a few degrees away from comfort for that pressure.

The obvious thing to be measured is body temperature, as an index of body heat loss. There are two complications: first, there is the problem of interpreting body temperature data in terms of heat loss and

in terms of the early hypothermia we are concerned with; second, there is the problem of what sensor, or rather where to put the sensor, to measure the core temperature which best relates to body heat loss.

Interpretation of Body Temperature Data

There is no simple relationship between body heat loss and change in deep body temperature. The complexity arises both because heat is lost differentially from the arms and legs compared to the torso and because the rate of heat loss has a strong influence on the resulting core temperature.

In the conventional description of cold exposure, thermal physiologists invoke the idea of a core and a shell. Heat loss is most rapid and occurs earlier from the shell, which is made up of the skin and the hands, feet, arms, and legs. The core is thought to be protected thermally, primarily through the mechanism of vasoconstriction, so that its temperature decreases much later than that of the shell. This concept is perfectly suitable for the kind of cold exposure that occurs with abrupt immersion of a nearly nude man in cold water. The concept does not apply nearly so neatly to immersion in cold water of a suitably protected man, like a diver. The thermal barriers in his clothing, and the fact that he is active, both modify the core-shell idea. A more serious problem is that it is hard indeed to connect the quantity of body heat loss with what particular temperature changes occur where, as the cold exposure continues.

The second complication is only just being recognized as important. For some time now we have been studying with a suit calorimeter the relationship between body heat loss measured by the calorimeter and the change in surface and core temperatures. What we see is that the faster the rate of heat loss, the quicker and farther the core temperature drops. Conversely, the more attenuated the heat loss, the smaller the drop in core temperature for a given quantity of heat lost.

To illustrate this second problem, consider the following two real situations. In the first case, a man falls overboard in cold water, say 10°C, and in something like a half hour his rectal temperature has dropped to 35°, he has been shivering hard for some minutes, and he is in considerable difficulty. We don't know precisely how much heat he has lost, but the best estimates are that it is in the neighborhood of 150 kcal. In the second instance, men in a swimmer delivery vehicle, rather well protected with wetsuits, can operate for six hours in water at 10°C. Their rectal temperatures drop by only 0.5 to 0.8°C. They are not shivering hard and they are maintaining reasonable performance levels. Every evidence suggests, however, that these men have lost something like 300 kcal.

Changing now from those real illustrations to laboratory simulations, in a moderately fast cooling experiment with our calorimeter we can remove 250 kcal of heat over two hours. During the second hour, the man is shivering violently and continuously, and his rectal temperature has fallen from 37 to 36°C. He reaches a tolerance point from fatigue and discomfort. We don't know how well he would perform, but probably not very well, during the last half hour. By contrast, we can pull out 300 kcal of body heat over a 6-to-8 hour period, during which time the man shivers not at all until the last 15 minutes, and then only mildly. His rectal temperature changes by only a half degree. He is bored but not thermally uncomfortable.

What we are aiming for in our laboratory investigation is a calorimetric description of men being cooled at different rates, from the most rapid to the slowest, with monitoring of body temperatures, oxygen consumption, and other physiological variables. When we have enough of these experiments, we hope to have enough data to make a useful mathematical model that predicts change in deep body temperature as a function of heat loss, and more particularly as a function of the rate of that heat loss.

In summary, it is not enough to simply know the body temperature. One has to know the temperature history and other things, like how much shivering has occurred.

Sensors for Measuring Core Temperature

Assuming that we know what to do with the information, the question still remains which site one should use to measure the core temperature. The practical choices are limited to the rectum, the gut, the ear canal, and possibly somewhere on the torso or head, with the relatively new "deep body temperature" devices.

The rectal temperature (T_{re}) is the standard measurement of core temperature, having a long history in physiology and medicine. Its acceptability to a working diver is very much at question. Physiologically there are problems with it because the temperature in the rectal compartment is the slowest and last to change.

Similar to the rectal temperature is the temperature somewhere along the intestinal tract (T_{gut}), which can be measured by the technique of swallowing a radio pill and having the signal picked up with an outside antenna. This technique has been recently improved considerably at DCIEM; Drs. Kuehn and Ackles are here at the conference and can speak further about this technique. Its acceptability is higher than that of a rectal probe. Apparently one can have an accurate pill which is cheap enough that it can be lost after use without worrying about it. I would like to be reassured as to the reliability of picking up the signal with the external antenna. I

also would like to see a good deal more experience with this approach in terms of the variation of the temperature signal depending upon the physical position of the pill at any given moment -- for example, how close it is to the front wall of the abdomen, which is relatively cool, versus how close to the liver, which is relatively hot.

A physiologically valuable site for measuring core temperature is the external auditory canal (T_{ac}). If we can assume that the diver's head is not specifically being cooled by the water, that is that he has on a helmet or a sufficient amount of insulation in a wetsuit, then T_{ac} is a good index of deep body temperature, somewhat better than rectal or T_{gut}. This temperature could be measured with a probe that is made part of a communications headset worn by the diver. The problems are primarily engineering ones, to make a reliable and acceptable probe of this kind.

Finally there are other possibilities for measuring deep body temperature, which will be discussed briefly at the end of this report.

In summary, sensors for measuring core temperature must be chosen on the basis of acceptability and physiological meaning. The interpretation of the data is a persistent problem, as reviewed in the previous section.

Recommendations

Trying to stay with what is available now and acceptable to a diver, the following four recommendations can be made:

Shivering. Shivering is usually a sign of considerable body heat loss, especially if the cooling has not been too rapid. Divers are surely aware of when they shiver, and the old hands probably know that when shivering reaches the stage of being uncontrollable, it is time to come out. Early shivering is, of course, sporadic and not very strong. It becomes more and more continuous. It also becomes harder to suppress by voluntary effort as cooling continues. No monitoring equipment is necessary, but of course it would be useful to have high quality communications with topside in order that a diver can report his degree of shivering.

Inappropriate behavior and fatigue. Assuming good voice communication with topside, a good monitor should be able to discover early signs of inappropriate behavior, like perseverance, errors in judgment, and so on. He also should be able, if he is in rapport with the diver, to establish that the diver is becoming fatigued beyond what is expected for the task he is doing. This recommendation ties closely to the topic being addressed by Dr. Bachrach; I have not seen his paper, but I would expect that a fairly specific set of ideas could be worked out for monitoring behavior in terms of early hypothermia.

Core temperature. The two sites recommended are auditory canal (T_{ac}) built into a headset, and an inexpensive and reliable radio pill for measuring T_{gut}. However, note the problems of interpretation of core temperature already discussed.

Training. For these three recommendations to be effective, I would hope that there could be organized experience in cold exposure for both divers and monitors. One has to develop an alertness to the possibility of hypothermia. It would be most useful to have Diving Medical Officers, Diving Supervisors, tenders, and divers taught what to look for in a purposeful way.

Near future developments

The ongoing project in my laboratory to quantify heat loss and body temperature change, leading to a mathematical model, should be of great use. This will make possible, we hope, a reasonable interpretation of core temperature data.

Another idea in the early stages of development is measuring not the result of heat loss but measuring heat loss itself from a suited diver. Heat flow disks are being used experimentally. Similar observations might be made whenever the diver wears a closed water tubing suit.

Farther out

Limiting myself to only one blue sky idea, and hoping to encourage others to pursue theirs, I briefly describe something we hope to try soon in our laboratory. A new kind of deep body temperature measurement has been developed in England. It relies upon a small heater and two temperature probes such that the heater reduces to zero the thermal gradient between the outer and inner surface of the device when applied to the skin. In other words, a condition of zero heat flow is established. The temperature of the sensor nearest the skin is now thought to measure something related to deep body temperature. The device has been applied on different parts of the torso so far. Several engineering improvements have been proposed. What occurs to me is that this approach could be used on the cranium, in the hope of measuring the deep temperature of the scalp, skull, and cerebral cortex. If there is danger in the behavioral changes of early hypothermia, then the cortex is the place from which one would expect changes to originate. The changes are presumably of thermal origin. If one could establish that there are small but meaningful changes in "deep body temperature" of the cranium, and further that they relate somehow to measurable changes in cognitive performance or behavior, one would be encouraged to pursue the idea further.

Discussion

The question was asked: If either rate of heat loss or core temperature could be measured but not both, which parameter would Dr. Webb prefer? He recommended heat flow and stressed the point by saying he would be much more concerned about the safety of a diver who had lost 100 calories in 20 minutes than about one who had lost 300 calories over 6 hours. As for monitoring methods, he felt that the use of heat flow discs may become useful once it has been connected to total body heat loss.

A discussion of the potential value of temperature measurements, notably rectal temperature, followed. Several discussants agreed that one drawback with rectal temperature was that it changes only with a considerable time lag behind core temperature, as measured by other methods such as the ingestible radio pill. Dr. Webb again emphasized that a good firm connection between temperature in the rectum and heat loss has not yet been established, but that core temperature readings (preferably by ear probe or radio pill) would gain in value if presented against time so as to indicate rate of change.

Dr. Elliott asked how important it would be to monitor the diver's temperature if he was provided with warming equipment, the output of which he could set himself so he was subjectively comfortable It was agreed that in this special case temperature monitoring would be of low priority. It was noted, though, that especially in a situation of slow cooling, a diver might approach a dangerously low body temperature without being fully aware of it.

One criticism of rectal temperature monitoring was that divers are unwilling to accept the procedure. Several discussants made the point, though, that making the diver accept any procedure essential for his safety should be only a matter of proper explanation.

Dr. Webb expressed some concern about a possible deviation from core temperature because a radio pill passing down the intestine would come close to the hot liver or the cool abdominal wall. Dr. Ackles stated that the radio-pill-thermometer developed at the Defence and Civil Institute of Environmental Medicine in Toronto showed good overall agreement with simultaneous rectal temperature readings, except that the latter would always show the previously mentioned time lag. He added that the pill will be available commercially at a price that definitely makes it disposable.

Would it make sense to monitor shivering? Not much, it was said, because if the diver shivers he would, in all likelihood, tell the tender that he was too cold. In addition, monitoring of shivering was deemed relatively difficult technically. Furthermore, although good

strong shivering is a reliable sign of major heat loss, it was stressed that especially in connection with slow cooling, a diver may slip into hypothermia without shivering in the process.

It was suggested that one attempted solution to the heat balance problem could be a predictive approach, using a model into which could be entered data about water temperature, the diver's thermal protection, etc. Dr. Webb maintained that there would be too many practical uncertainties, such as changes in insulating effect of wet suits with depth, leaks in dry suits, and so on and therefore the only reliable way to know anything about a diver's thermal status would be to measure it.

BIOELECTRIC INDICANTS OF DIVERS' ABILITY TO PERFORM USEFUL WORK

Robert S. Kennedy

The present paper will discuss the relationship between certain characteristics of eye movement and overall central nervous system status, beginning with the study of vestibularly induced nystagmus.

The relationship of eye movement to vestibular stimulation is well known and has been described many times (Kennedy 1972). Specifically, as the head moves to a new position, the eyes lag behind the skull and effectively permit one to continue looking at the starting point. This is not a passive response due to inertia nor is it due to visual fixation, although both of those factors are present. Rather, the slow compensatory deviation of the eyes in the skull (which served to keep the eyes fixed over the earth) is caused directly by a vestibular signal and occurs also in the dark. This eye movement is the slow phase of nystagmus and has as its probable site of origin the vestibular nuclei (Gernandt 1959). The second phase -- the fast phase -- is considered to be compensatory to the slow.

In a 1965 psychophysiological review Guedry referenced about 20 papers in which the subject's mental state modified recorded vestibular nystagmus. Gernandt (1959) has suggested that the fast phase is influenced by the reticular activating system (RAS) and Wolfe (1966) has retrieved habituated nystagmus by RAS stimulation. Further, it was shown that the fast phase was absent in patients who lacked a pontine reticular formation (Daroff and Hoyt 1971). Therefore, it was decided to expose a large group of people to vestibular stimulation while recording nystagmus and measuring their performance on a vigilance task. The hypothesis had been that vigilance performance would bear some relationship to the quality of the fast phase. In other words, knowledge of the fast phase could be predictive of the vigilance performance.

Vigilance Test

Three tones that were clearly audible and distinguishable were presented randomly for an hour. The subject's task was to monitor the low (8 pulses/minute) and middle (6 pulses/minute) and ignore the high (5 pulses/minute) tones. Each occurrence of a tone was mentally counted and a key was pressed when a given tone had been sounded four times. The subject then began again for that tone. The subject's score was percent correct for each 5 minute period. Figure 1 shows the temporal distribution of tones and Fig. 2 shows the expected values for six versions of this test. The one labeled "two channel complex" is described above and was employed in the eye movement experiment.

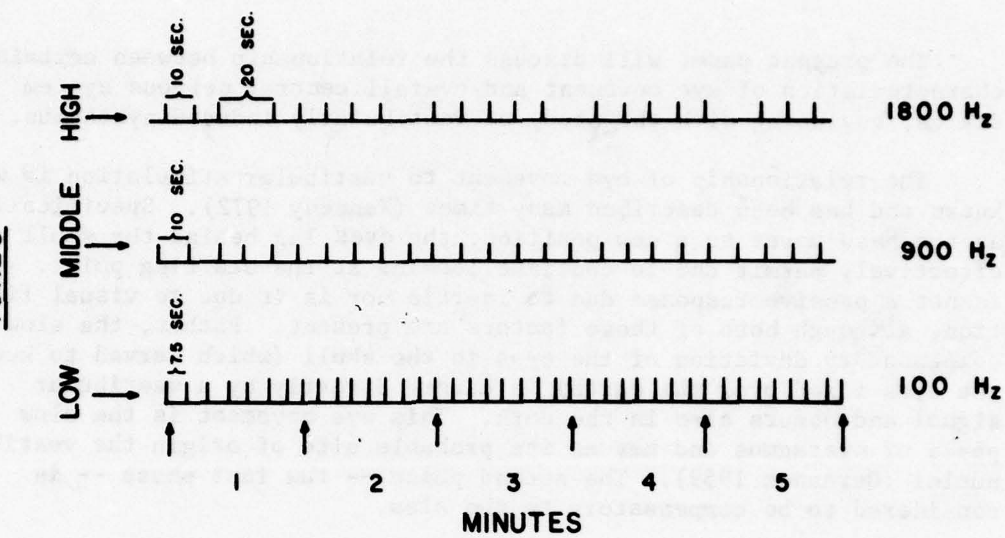

Fig. 1. Five-minute swatch of temporal distribution of tones.

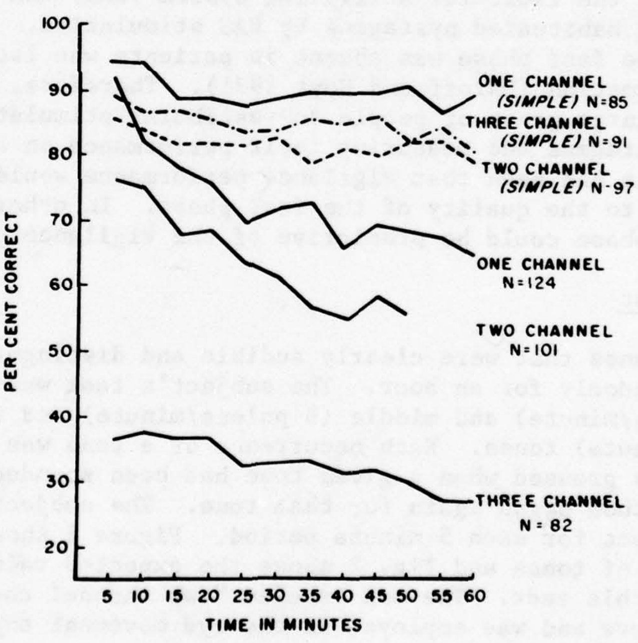

Fig. 2. Performance on 6 different versions of a vigilance task.

Nystagmus

The subject was dark-adapted for 20 minutes to partially control for fluctuations in the cornea-retinal potential (Kennedy 1972) and was then exposed to sinusoidal oscillation about the spinal axis for 50 minutes. Stimulus parameters were a 75° displacement every five seconds (0.2 Hz; 46.8/sec peak velocity and 58.5°/sec^2 peak angular acceleration).

Lateral eye movements were obtained by standard electrooculographic techniques, with electrodes at the outer canthi. Pre- and post-calibrations were not significantly different. One-hundred fifty healthy student pilots comprised the experimental population; 50 were tested for vigilance only, 50 for nystagmus only, and 50 for both.

Scoring

The procedure used is best described as an examination of the fast phase. In general, 100% of a cycle with good nystagmus received a 10, and almost no nystagmus was scored 1.0. Two lower categories were used, 0.5 and 0.1, for final determinations. The reliability of the method was good ($\underline{r}$ = 0.95). It should be noted that while using mainly fast phase (presence/absence) in scoring, Wendt (1965) felt that other eye movements qualified as habituation, particularly with shorter arcs of oscillation.

RESULTS

The next slide (Fig. 3) shows the performance of these three groups. The vigilance performance of both groups was not significantly different but the quality of nystagmus in the group without the vigilance task decayed more rapidly than for those who did mental work. This is what one would expect from the literature, as reported by Guedry (1965). Vigilance and nystagmus follow the same course ($\underline{r}$ = 0.93).

To determine whether the vigilance performance of a particular subject could be predicted from his nystagmus at any time, each subject's scores were correlated within a session. The average of these correlations was $\underline{r}$ = 0.30 and was significant (P < .0001). Another correlation was obtained for the 500 matched scores (50 subjects and 10 5-minute time frames). This operation is statistically indefensible but has a practical utility for vestibular investigators. For instance, one may wish to predict a person's vigilance score regardless of who he is or what time in the session it is; this correlation is $\underline{r}$ = 0.49 (P < .001).

In conclusion, I feel that under the experimental conditions used, a general correspondence exists between the quality of the fast phase and the alertness measured by a vigilance task. This correspondence supports what would be expected from the neurophysiological literature regarding the pathways of the fast phase and has both applied and

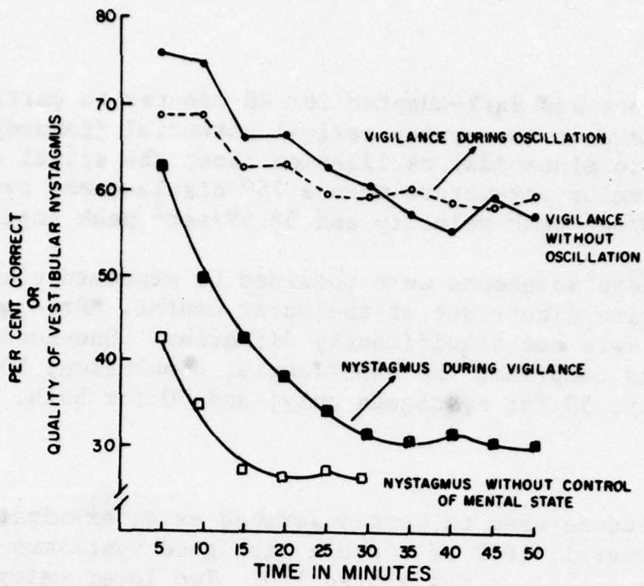

Fig. 3. Nystagmus and vigilance in 3 different groups.

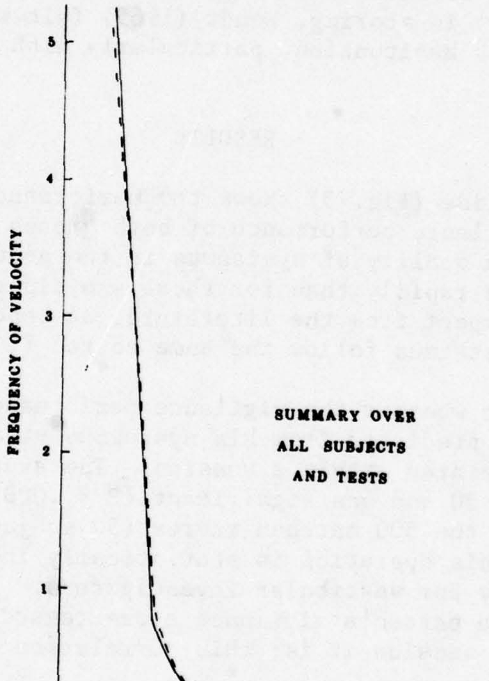

Fig. 4. Spectral density of eye movement velocities over all 6 subjects.

scientific implications. It suggested that (1) perhaps the fast phase of vestibular nystagmus could be used as a quantitative and independent index of arousal, so that a person's performance in a job could be monitored without interfering with his work; and (2) perhaps other quick flicks of the eyes (optokinetic fast phase, involuntary movements and microsaccades) reflect similar mechanisms. If true, they also could provide indicants of the level of arousal. If the latter could be shown to be so, it might be possible for a computer to analyze the eye movements of a pilot or diver and when they meet a criterion level of drowsiness, inform him of this condition and remove him from the situation. Because of these results, the second phase of this experiment was begun, in which no vestibular stimulation at all was used but the subjects merely sat in the dark, performing the same two channel monitoring tasks and again recording movements, with some variation. Two recording techniques were employed, surface electrodes as before, with EEG-type electrodes at the outer canthi, and on infrared scleral reflection device. The comparisons of these two methods will be reported elsewhere and need not be discussed further, except to indicate that each has different characteristics that would make it more or less feasible depending on the working conditions, diving conditions, etc. Second, an analysis of eye movement data that differed from before was undertaken. It was felt that the reason for the previously obtained relationship between eye movement and performance occurred because something happened relative to the fast phase, whereas the slower eye movements remained essentially the same, albeit with a slight change in phase and in gain.

In a previous study the data were all scored by hand and inspection revealed that a brisk, strong, fast phase contributed to alert scores and what appeared to be slower fast phases occurred when vigilance was poor. It was hypothesized that the briskness or velocity of the fast phase of eye movements may be generally indicative of alertness or of overall potential for work. Therefore, a new method for scoring eye movements was employed: a spectral analysis of eye movement velocities, sampled 100 times/sec directly from the infrared eye movement recording device was performed. These were totalled by computer and printed out as scores each minute. The next figure (Fig. 4) shows the data for the entire experiment. Note that nearly all the eye movement power is found in the range 0 - 100°/sec. Figure 5 shows the same type of information, but in this case early and late eye movement are separated for the various ranges of velocities. It may be seen that the 100° - 200°/sec category is changed so that there are fewer "later" than "earlier" movements and the converse occurs with 0 - 100°/sec eye movements. It should be emphasized that while these differences are small, they are also highly reliable and are therefore likely to be real. It should also be noted that these differences and other data to be presented are consistent within subjects as well. The next figure (Fig. 6) shows the eye movement data for a single channel performance -- the simplest test comparing early and late movements. It may be seen that later eye

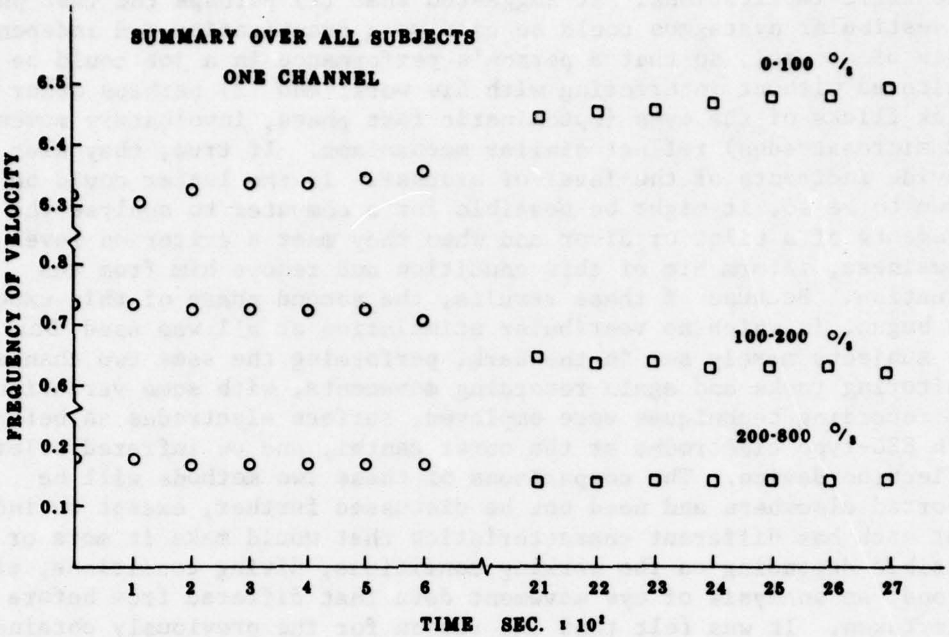

Fig. 5. A comparison of early and late eye movement velocity categories in all vigilance tasks combined.

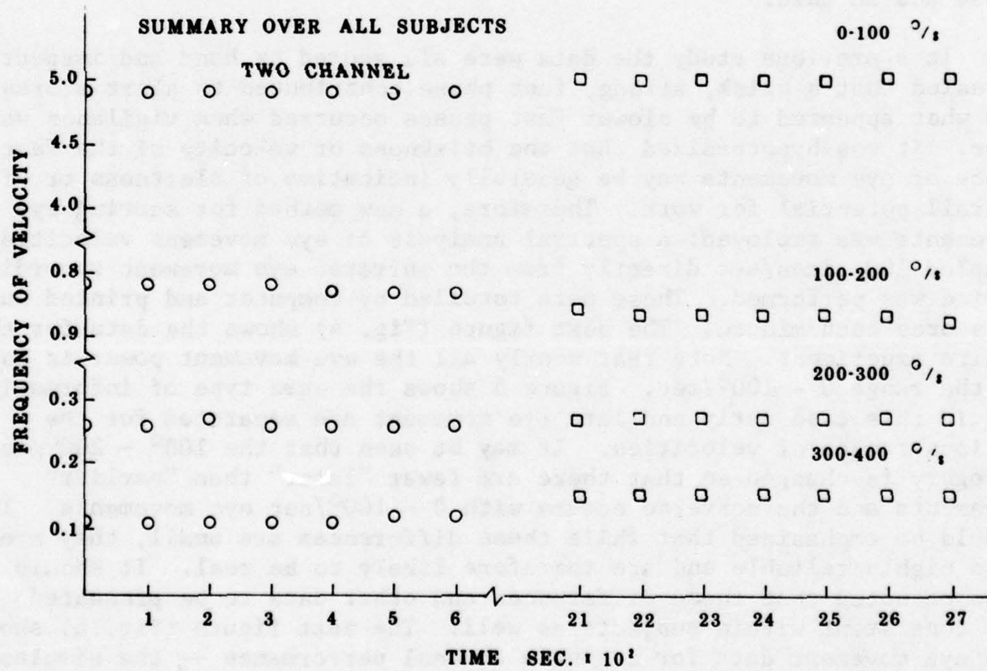

Fig. 6. A comparison of early and late eye movement velocity categories in the 1-channel vigilance task.

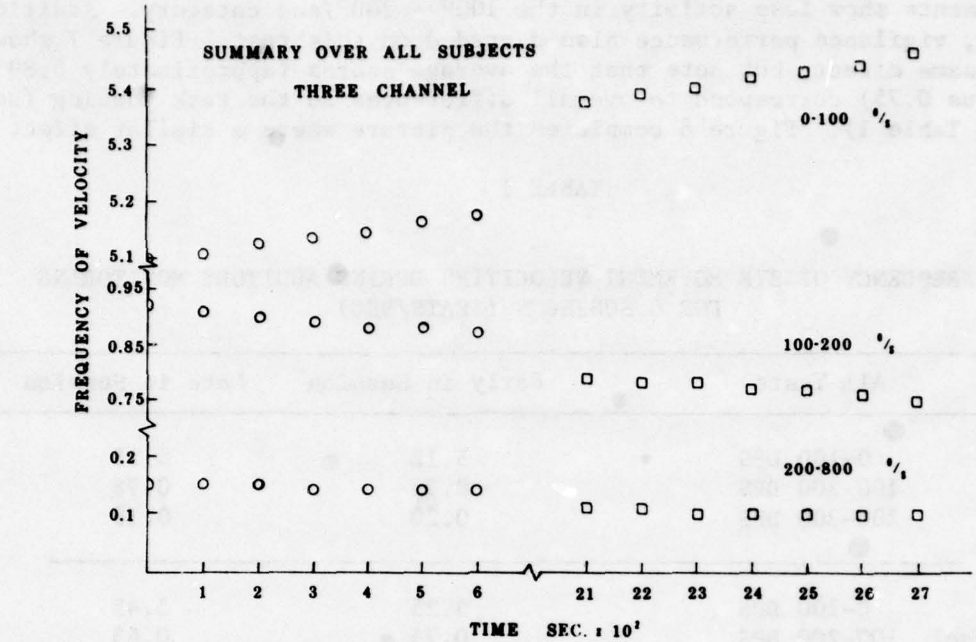

Fig. 7. A comparison of early and late eye movement velocity categories in the 2-channel vigilance task.

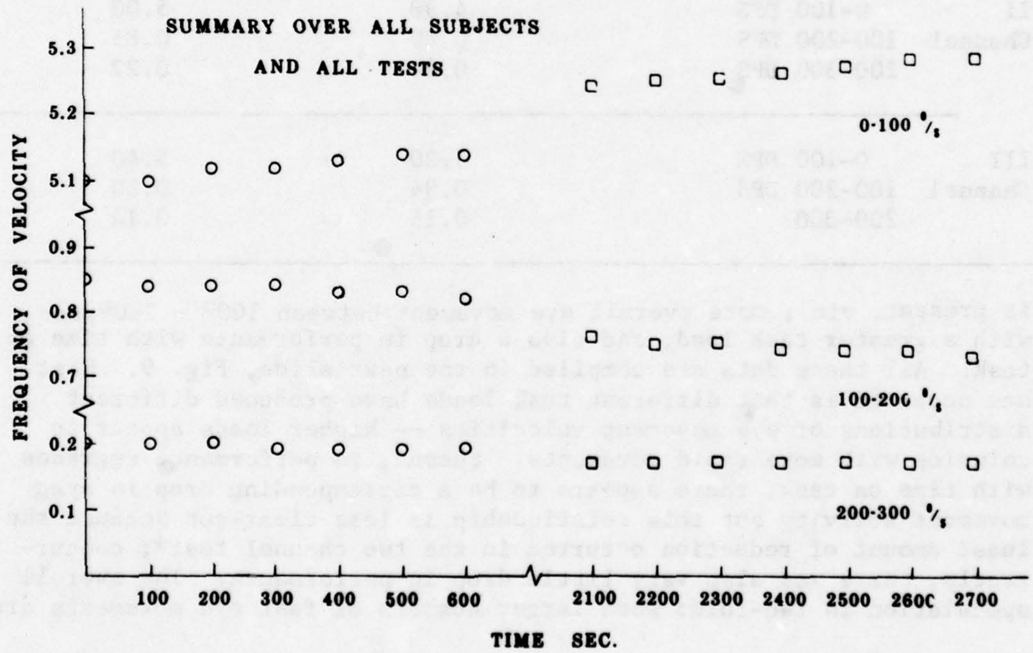

Fig. 8. A comparison of early and late eye movement velocity categories in the 3-channel vigilance task.

movements show less activity in the 100° - 200°/sec category. Additionally, vigilance performance also degraded on this test. Figure 7 shows the same effect, but note that the average scores (approximately 0.89 versus 0.75) correspond to overall differences in the task loading (see also Table 1). Figure 8 completes the picture where a similar effect

TABLE 1

FREQUENCY OF EYE MOVEMENT VELOCITIES DURING AUDITORY MONITORING FOR 6 SUBJECTS (BEATS/SEC)

	All Tests	Early in Session	Late in Session
	0-100 DPS	5.12	5.25
	100-200 DPS	0.85	0.78
	200-300 DPS	0.20	0.19
I	0-100 DPS	5.25	5.45
Channel	100-200 DPS	0.75	0.65
	200-300 DPS	0.19	0.17
II	0-100 DPS	4.90	5.00
Channel	100-200 DPS	0.89	0.85
	200-300 DPS	0.26	0.27
III	0-100 DPS	5.20	5.40
Channel	100-200 DPS	0.94	0.80
	200-300	0.15	0.14

is present, viz., more overall eye movement between 100° - 200°/sec, with a greater task load, and also a drop in performance with time on task. All these data are compiled in the next slide, Fig. 9. What has occurred is that different task loads have produced different distributions of eye movement velocities -- higher loads appear to coincide with more rapid movements. Second, as performance degrades with time on task, there appears to be a corresponding drop in eye movement activity but this relationship is less clear-cut because the least amount of reduction occurred in the two channel test*; concurrently, there was also very little drop in performance. The overall speculation is two-fold: when larger numbers of fast eye movements are

*See Fig. 10.

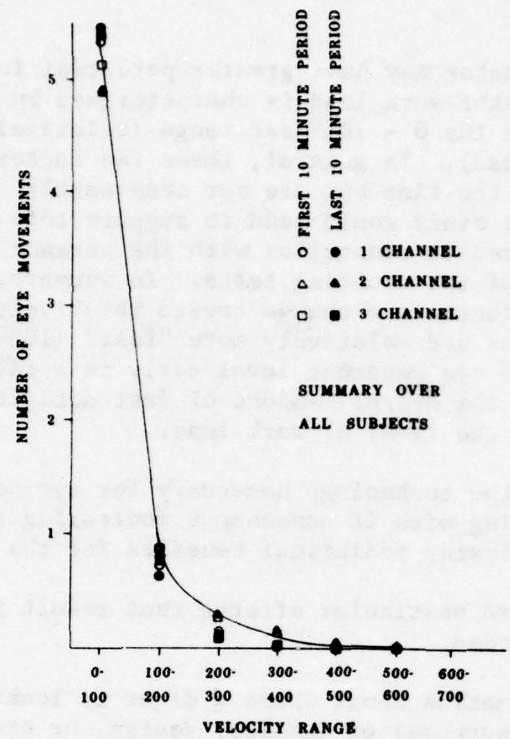

Fig. 9. A comparison of early and late eye movement velocity categories on 3 different vigilance tasks.

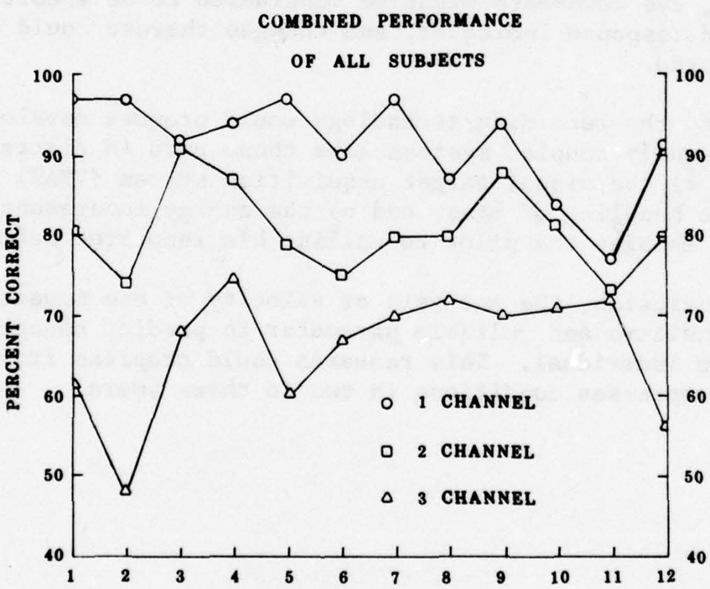

Fig. 10. Performance in percent correct on 3 different vigilance tasks.

available, the operator may have greater potential for information load; second, operator work load is characterized by the lower number of eye movements in the 0 - 100°/sec range (relatively more of them indicate a light load). In general, these two factors would be correlated most of the time but are not necessarily. The eye movement data of the present study would tend to support this notion, particularly when considered in connection with the percent correct scores on the various forms of the counting tests. In summary, in all cases with time on task there is a change toward relatively more "slow" (0 - 100°/sec) later and relatively more "fast" (100° - 200°/sec) early. Second, the eye movement level early in a test is consonant with this finding; the overall amount of fast activity (see Table 1) is proportional to the level of work load.

In addition, the technology necessary for eye movement measurement might also bring with it assessment monitoring techniques that would have the following additional benefits for the working diver:

First, untoward vestibular effects that result in nystagmus could be recorded.

Second, information about where a diver is looking could be recorded for purposes of display, design, or other training of diver work operations.

Third, eye movements might be considered to be a cortical-evoked response indicator, and changes thereto could be monitored.

Fourth, the recording technology would promote development of visually coupled systems like those used in aircraft, viz., a) the visual target acquisition system (VTAS) for remote handling of mass, and b) the energy management display which enables the pilot to utilize his resources better.

In conclusion, the analysis of velocity of eye movements may be a useful, sensitive and reliable parameter to predict changes in the state of an individual. This research could progress from a hyperbaric chamber to open-sea conditions in two to three years.

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Discussion

Dr. Berghage advised against performance tests under in-sea conditions if the test would distract the diver from the original task he was sent down to complete. Dr. Kennedy agreed and added that for specific in-sea performance he proposed that eye movement patterns should first be checked against suitable tasks in the laboratory. The laboratory tasks would resemble those to be performed in the sea, and changes in eye movement activity would be related to deterioration in performance on these tasks. Later, in actual diving, the eye movements would be recorded to make predictions about the diver's ability to perform on the sea bottom.

Dr. Kennedy indicated that this type of monitoring would be most valuable as a good overall index of arousal and performance when the diver was performing a task of a more complicated, decision-making nature, and that it would have very low practical utility for predicting performance in tasks principally involving physical exertion.

In response to questions about the practicality of this method in real diving, and specifically about the way the signal of eye movements would be generated during in-sea conditions, Dr. Kennedy answered that there were basically three methods available for recording eye movements: surface electrodes, recording of infrared reflection (from the sclera, for instance) and television. Dr. Kennedy added that he expected this technique to be applicable about three years from now.

Comments from the discussants varied. Some doubts were expressed that this method would ever become practical for diver monitoring because of its technical complications. Other discussants maintained that, in view of research by another group that showed a relation between eye movement activity and learning capacity on a given task and decrement in function, this looked like a very promising field, although it was clearly still at the research stage.

PERFORMANCE DECREMENTS - A TOOL FOR DIVER MONITORING

Glen H. Egstrom

The imperatives of diving safety make it clear that current information on the functional status of the working diver is essential if early warning of reduced diver effectiveness is to be determined. Although there is general agreement on the desirability of monitoring current diver status, there has been little in the way of implementation relative to day to day diving operations. This lack of implementation does not appear to be due to a lack of concern for diver safety but rather to a lack of reliability/validity data for the techniques that have been developed. Though many of the techniques can identify catastrophic malfunctions, they are less sensitive in predicting an impending problem.

This problem of prediction validity becomes very important when the efficiency and effectiveness of diver performance is considered. The high degree of specificity that marks the performance of a particular diver using a particular life support system in a variable work environment makes it virtually impossible to develop a prediction system with micrometer accuracy. As monitoring techniques improve and the data base increases, however, the accuracy of a prediction could improve dramatically.

The study of man's performance as a worker in the undersea environment has been focused on a wide variety of discrete tasks under laboratory conditions. An excellent summary of these measurements can be found in the performance chapter in the <u>Underwater Handbook</u>. The summaries are separated into performance dimensions and stress characteristics with attendant findings. The findings are admittedly a compilation of a patchwork of information on the dimensions and characteristics of diving. Though it is unfortunate that there is so little in the way of data that could be useful in field operations, this is nevertheless the case. There are currently no performance criteria that have an established reliability and validity for day to day diver performance monitoring.

The working diver routinely undertakes tasks requiring a wide variety of skills, ranging from fine digital manipulation to "mule hauling" large objects. The diver moves in a multi-dimensional setting, changes his body orientation constantly, and is usually involved in a "total" task. The amount of learning experience and reinforcement also varies considerably with the specific task.

The problem, then, centers upon the fact that performance is extremely variable and working divers make highly specific adaptations to the demands imposed by the task, the environment, the life support system, the tools, and the state of the organism.

During the early 1970's, the Office of Naval Research funded a research program at University of California Los Angeles (U.C.L.A.), which studied underwater work performance and work tolerance. At the outset it was obvious that the concept that diving was a generalized skill that could be applied to any underwater work situation had to be modified to accommodate the fact that diving per se was a means of supporting life and transporting the diver to a worksite where the "real world" task would require all of the art and the science associated with any specialized work function. Divers could be expected to execute efficiently and effectively those functions that were well learned and periodically reinforced under "real world" conditions.

The wide array of studies have demonstrated that decrements in performance can be anticipated in the majority of underwater work efforts. Changes in sensitivity to touch, vibration, pressure, postural control, etc., appear to be significant. Decreases in strength, torquing, work capacity, lifting and pulling, dexterity, assembly and tracking, and coordination have been identified. Thus cognitive, psychomotor, sensory-perceptual and work capacity are variable when affected by the stresses of the work environment and the level of adaptation of the diver.

The early U.C.L.A. effort to develop some predictive insight into this complex problem resulted in an attempt to quantify the decrements found in underwater work. This effort accepted the fact that any such predictions would be gross in nature and would require extensive validation and refinement. In the light of present day problems, the concept appears worthy of review.

At the outset diver performance was divided into four broad classifications of cognitive, psychomotor, sensory-perceptual and work capacity. These performance categories were then evaluated in terms of the degree of anticipated decrement as a function of the effective environment in which the diver was expected to work. This evaluation was projected into a work tolerance matrix that was part of a generalized decision system.

The following diagrams identify the proposed methodology for using the work tolerance tables under development. The first diagram, a schematic of the immediate physical and physiologic data, serves two functions. First, it provides a current picture of the diver and his environment, and second, it provides information that can be used to predict decrement. The examples given are incomplete. By way of example, however, the effective temperatures would be the product of such variables as water temperature, diver insulation, metabolic output, exposure time, etc., and would exert differing effects on the periphery and the core.

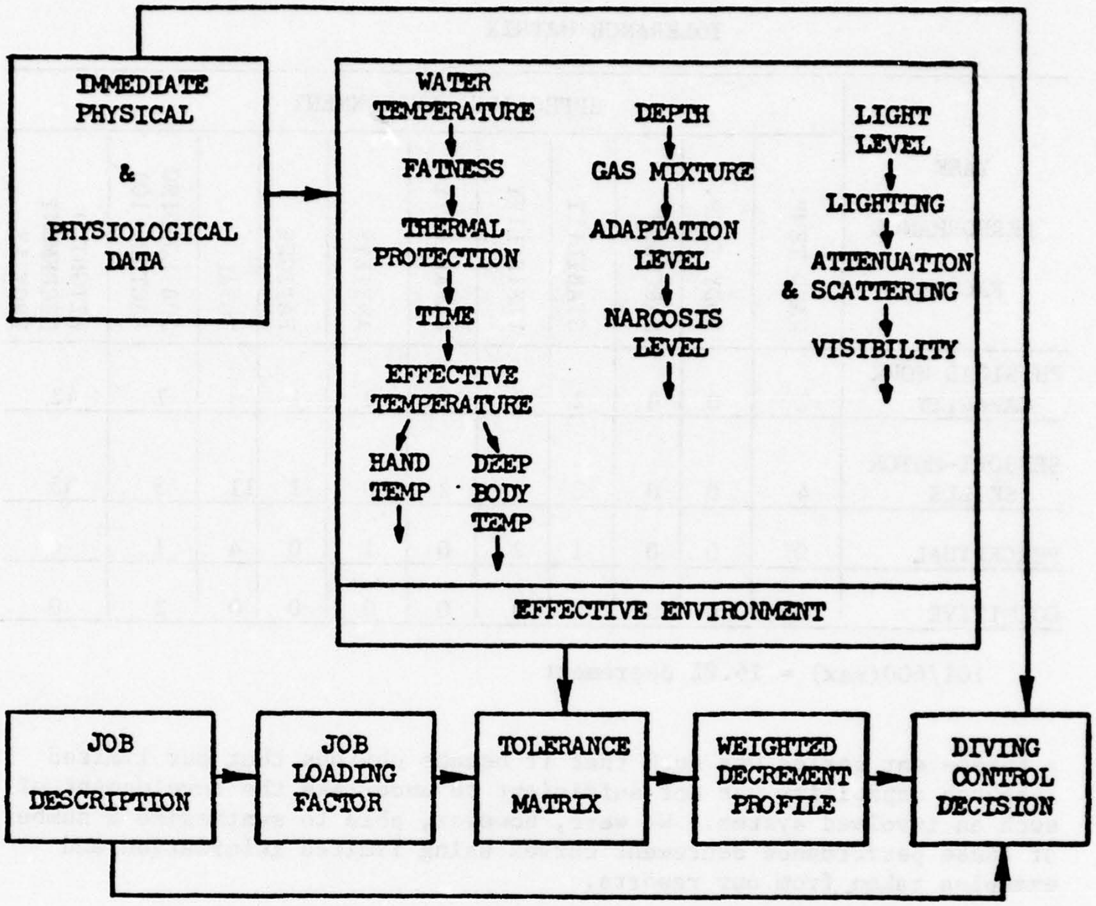


Diagram 1. Generalized Decision System

In the tolerance matrix, Table 1, the influence of the effective temperature was ranked from 1 to 5, with 5 being the highest expected decrement. Each of the environmental decrements would then be treated in a similar manner and accumulated. The sum would then be multiplied by a job loading factor. This factor would be drawn from the available literature, work records, and diving logs, and would represent the overall job difficulty on a scale of 10. The resultant weighted decrement profile would then be calculated, totaled, and evaluated as a part of the decision apparatus. The decision to reject or perform the dive or, if the factor changed during a dive, to abort a given dive, would then be made. The example demonstrated in Table 1 represents a routine assembly task in cold, shallow water with fair visibility, some swell, and low risk. The overall decrement could then be determined to be an acceptable or unacceptable risk. Unfortunately, our experience over

TABLE 1

TOLERANCE MATRIX

TASK PERFORMANCE FACTORS	EFFECTIVE ENVIRONMENT										
	HAND TEMP.	BODY TEMP.	NARCOSIS	STABILITY	VISIBILITY	CAPABILITY	ANXIETY	FATIGUE	TOTAL	JOB LOADING FACTOR(/10)	WEIGHTED DECREMENT PROFILE
PHYSICAL WORK CAPACITY	2	0	0	2	0	1	0	1	6	7	42
SENSORI-MOTOR SKILLS	4	0	0	3	1	2	0	1	11	5	55
PERCEPTUAL	0	0	0	1	2	0	1	0	4	1	4
COGNITIVE	0	0	0	0	0	0	0	0	0	2	0

101/600(max) = 16.8% decrement

a three-year period was such that it became obvious that our limited research capability was not sufficient to undertake the development of such an involved system. We were, however, able to synthesize a number of these performance decrement curves using limited information and examples taken from our reports.

Figure 1 shows an example of the data derived in controlled fresh-water studies with 1/4" neoprene wet suits. The tasks used were similar in general design but not identical. Standardized data collection procedures and more data could significantly alter the envelopes, and would yield greater precision (1).

Data for the development of such curves is often acquired by establishing a behavioral research protocol involving check lists, error quantification, video tape recordings, time of accomplishment differentials, etc., applied to a given task and life support system. An obvious weakness in this approach lies in the assumption that the experimental conditions are comparable. If standardized procedures were followed for data acquisitions, the decrement curves would be more valuable.

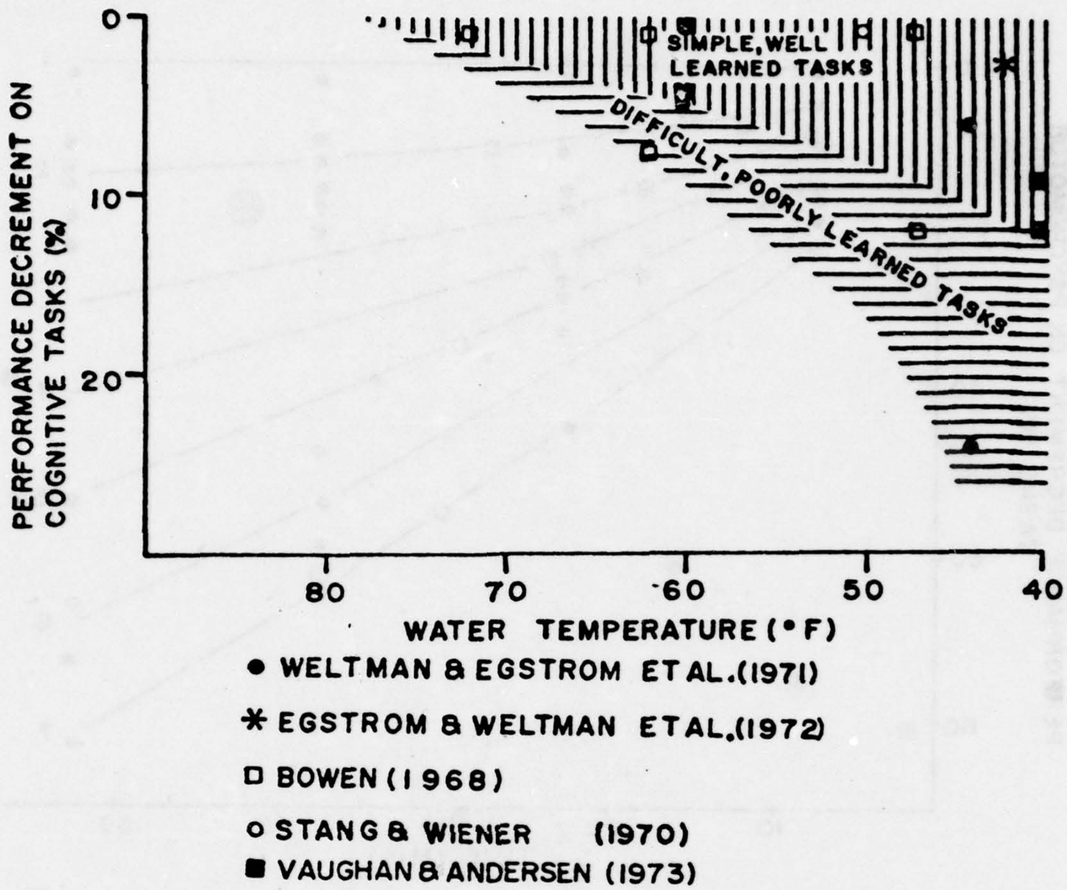
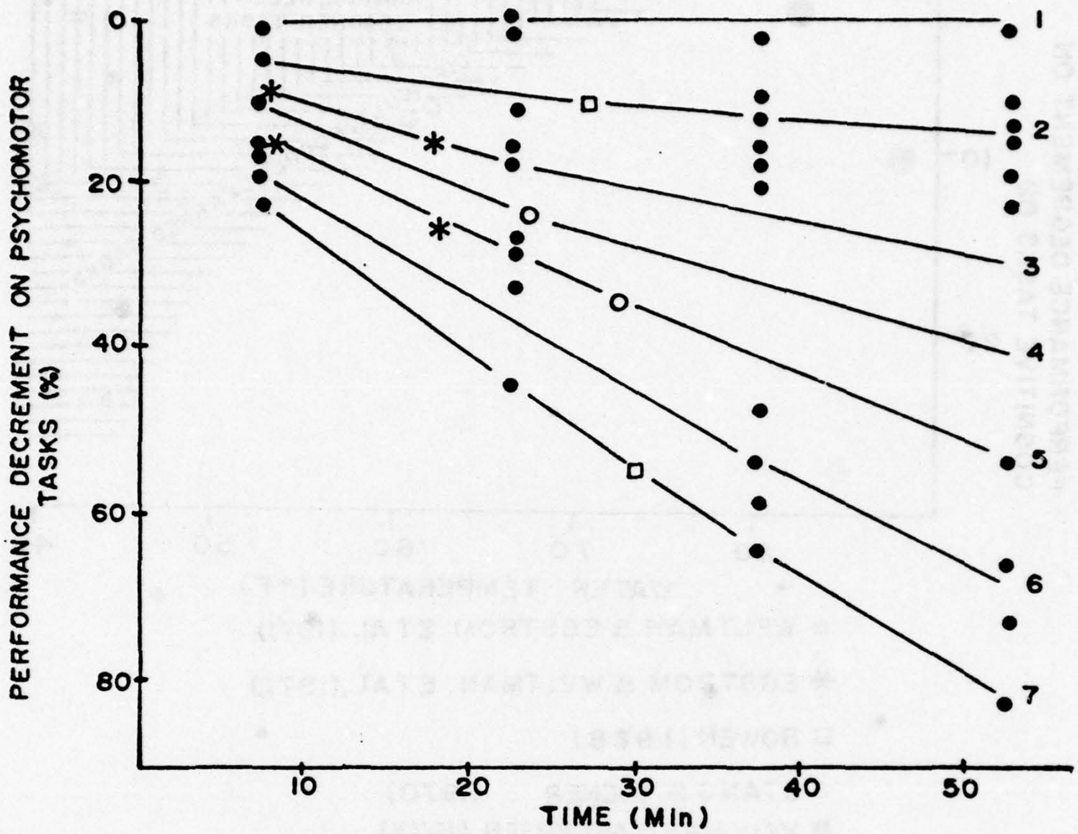


Fig. 1. The effect of water temperature on cognitive task performance.

In light of the lack of standardized data for the variations in underwater work circumstances, some alternatives are considered.

One alternative with some practical overtones would be to train diver-tender teams to the level at which the tender, watching a video monitor or even listening on the com box, would be sensitive to changes in diver behavior. A sensitive tender would be able to recognize degraded performance in much the same manner as the athletic coach can spot minor performance flaws in high level athletes, so that corrective action can be taken before serious problems occur.

Another alternative would require that a base line of performance be established for each diver on a hierarchy of tasks. Significant departures from this performance level would be cause for corrective action. This type of monitoring could be correlated easily with physiologic parameters such as heart rate change, respiration rate change,



PROPER DECREMENT CURVE

TYPE TASK	WATER 70	TEMPERATURE 60	50	40
FINE DIGITAL MANIPULATION	1	5	6	7
SIMPLE ASSEMBLY	1	2	4	6
GROSS BODY & POWER MOVE.	1	2	2	3

● STANG & WIENER (1970)
* BOWEN (1968)
O WELTMAN & EGSTROM ET AL.(1970)
□ WELTMAN & EGSTROM ET AL.(1971)

Fig. 2. Effect of exposure length on psychomotor task performance in cold water (1).

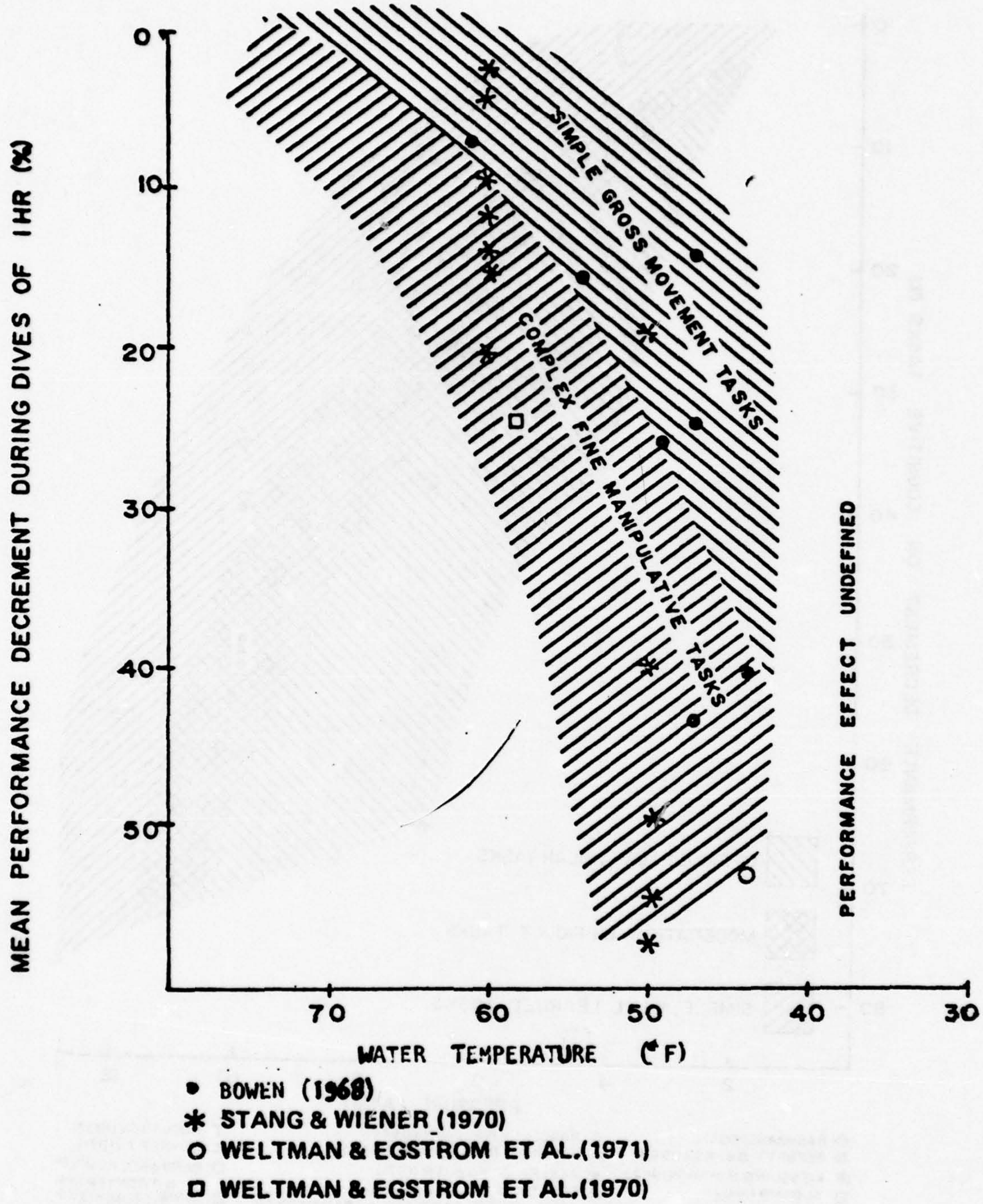


Fig. 3. Average decrement in psychomotor performance during hour exposures to cold water (1).

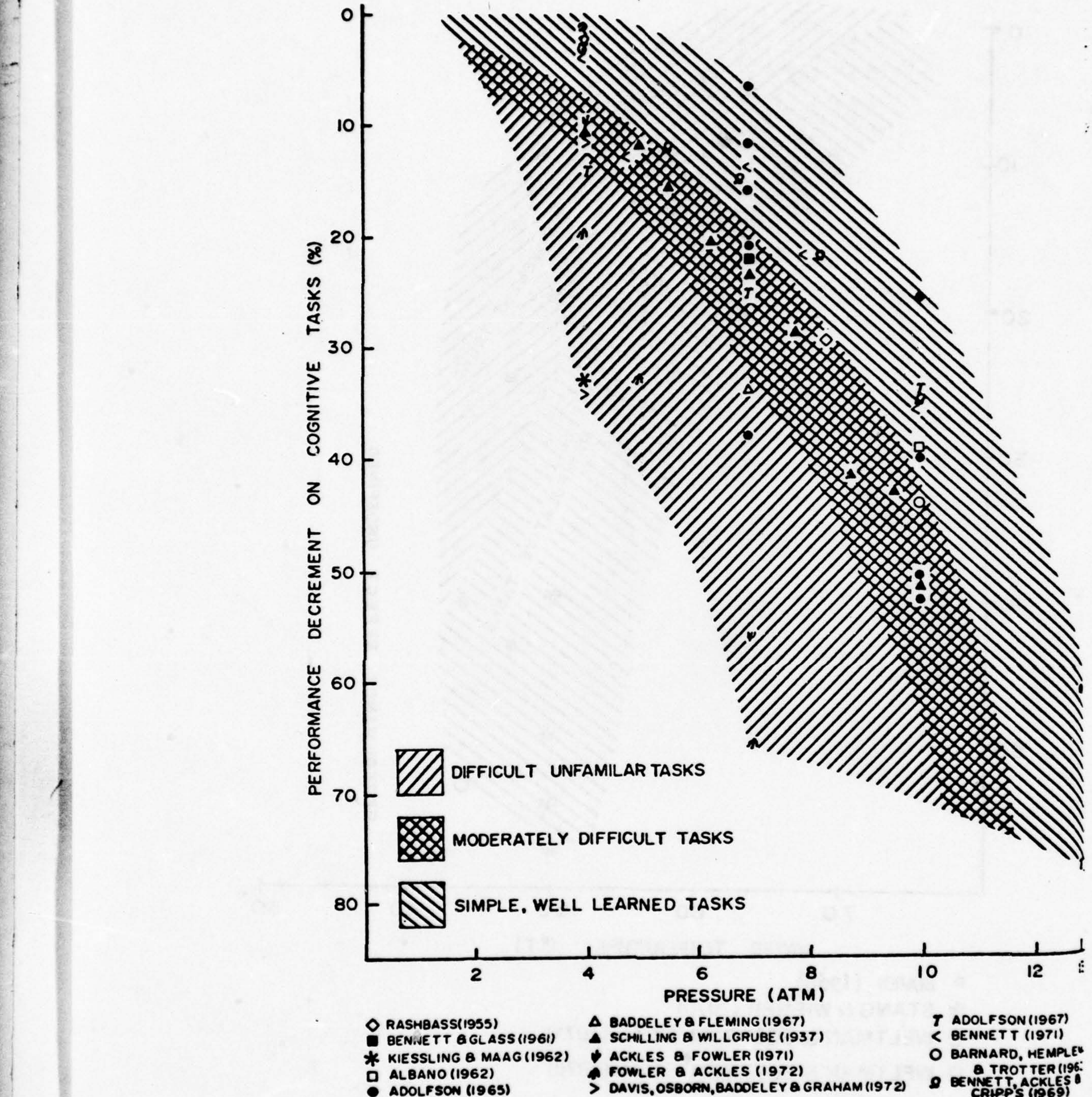


Fig. 4. Narcotic effect of air at high pressure on cognitive task performance. (1).

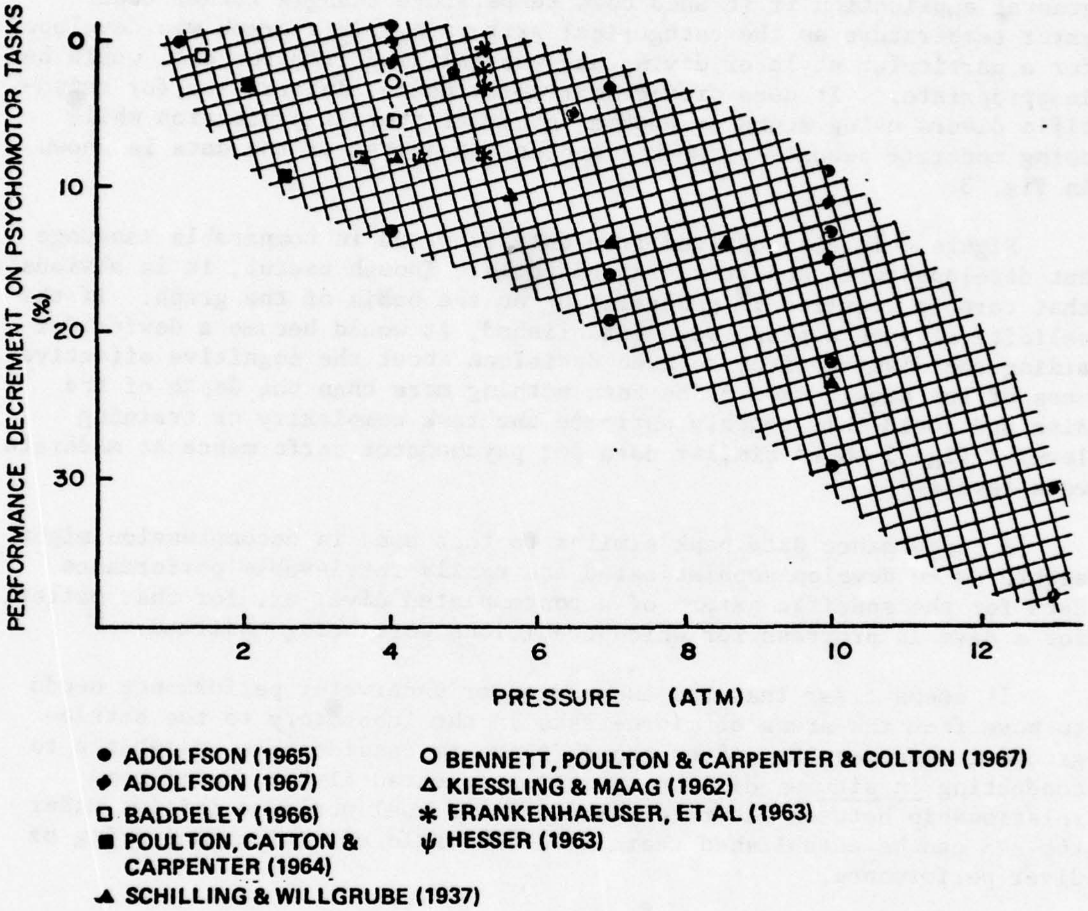


Fig. 5. Narcotic decrement of hyperbaric air on psychomotor performance (1).

or core temperature change, or behavioral changes such as error magnification, time delays, or other quantifiable manifestations of degraded performance.

Figure 2 shows another attempt to develop a tool for prediction. Again, the wet suited divers were performing different tasks, but the work levels were moderate and the thermal protection used was comparable. There is little question that this type of treatment would have greater general application if it used core temperature changes rather than water temperature as the categorical criterion. This graph was developed for a particular style of diving and generalizing from the data would be inappropriate. It does provide extremely useful information for scientific divers using scuba or hookah in normal thermal protection while doing moderate amounts of work. Another treatment of the data is shown in Fig. 3.

Figure 4 is also derived from data reported in comparable language but developed with non-standardized tools. Though useful, it is obvious that care is required in generalizing on the basis of the graph. If the validity of such a graph were established, it would become a device for aiding the diver-monitor to make decisions about the cognitive effectiveness of the diver, even if he knew nothing more than the depth of the dive and could only roughly estimate the task complexity or training level. Fig. 5 shows similar data for psychomotor performance at moderate work levels.

A performance data bank similar to that used in decompression might enable us to develop sophisticated and easily retrievable performance data for the specific nature of a contemplated dive, or, for that matter, for a dive in progress for which conditions were being modified.

It seems clear that the assessment of underwater performance needs to move from the arena of micro-tasks in the laboratory to the battleground of macro-tasks. Even though there is considerable resistance to conducting in situ studies on operation-oriented divers, until some relationship between laboratory studies and real world activities under the sea can be established there will be little effective monitoring of diver performance.

This material has been presented in the hope that it will provide a stimulus for a discussion of the feasibility of diver monitoring in underwater human performance.

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Discussion

Dr. Barnard observed that the approach described by Dr. Egstrom may be especially helpful in educating dive supervisors. Dr. Elliott saw particular value in the systematic quantitative approach to defining job-loading factors, because it would strengthen the diving supervisor's position on occasions when he has to tell the drill manager it is unsafe to put divers in the water.

Another discussant commented that to get a job done, it may be necessary to use a diver one knows will perform poorly, possibly making up for that by allowing him more time at the job. The standard predictions would then apparently be inapplicable. Dr. Egstrom agreed and noted that if one could anticipate or see increasing degradation in performance, one would have to conceive of the situation as one of increasing risk, which would, in turn, introduce the question of where to draw the line (a question for which there is no absolute answer). Dr. Egstrom added that this would also be a situation where alarms would be important. If, for instance, the pulse rate shot up to 170, it would be dangerous to require the diver to sustain that for any length of time. The control decision would have to be to abort the dive, or at least to back off temporarily.

Dr. Egstrom held that there were many reasons we have not advanced very far yet in developing the predictive system he advocates. But he was of the opinion that the tools for working it out are available, and that there is no reason why fear of taking on the problems of a large statistical array should hold us back.

His suggestion that monitoring divers would allow the accumulation of a data base (apart from making the dive at hand safer) met with a variety of responses. Dr. Bennett explained that large diving firms have indeed indicated a willingness to collaborate with researchers interested in monitoring divers under in-sea conditions. Referring to experience with collection of decompression data from operational dives, Dr. Thalmann expressed pessimism about the possibility of systematizing and evaluating performance data obtained under the same conditions because of the large number of variables. He suggested that more emphasis be placed on laboratory work to obtain the necessary data base. Dr. Egstrom responded that operational data would be required to substantiate the laboratory data.

A NEW METHOD FOR MEASURING PULMONARY VENTILATION*

Mark E. Bradley and Charles H. Robertson, Jr.

We have developed a model of chest wall movement which assumes that the rib cage and abdomen behave like elliptical cylinders, with freedom of movement laterally as well as in the anteroposterior (A-P) dimension. Using this model, a computerized method of measuring ventilation with magnetometers placed anterio-posteriorly and laterally on the rib cage and abdomen is described. Calibration is performed on normal breaths during rebreathing, avoiding the "isovolume maneuver" required by most previous techniques and allowing the use of naive subjects.

Under non-immersed conditions in subjects of widely varying body habitus, this method predicted lung volume change accurately during quiet breathing ($\underline{r}$>0.95, variance 0.5%), and during vital capacity maneuvers $\underline{r}$>0.97, variance 1.2%).

This model has the capacity to measure accurately the fractionation of ventilation between rib cage and abdomen-diaphragm movements, but it does not require the use of the awkward "isovolume maneuver," which demands a highly trained subject. In non-immersed subjects sitting upright, we found that 74% (range 47 - 91%) of the volume change was accomplished by the rib cage and 26% by the abdomen - diaphragm. This is similar to previous estimates of the fractionation by other techniques.

Our method appears to work well in situations which involve increased respiratory effort. Subjects performed forced vital capacity maneuvers and breathed against external inspiratory and expiratory resistances. Using the calibration parameters generated from the normal breaths during rebreathing, there was good correlation between plethysmographic volume change and the volume predicted by the four-channel magnetometers during the forced vital capacity maneuvers ($\underline{r}$>0.98). Ventilation measured in subjects breathing through expiratory and inspiratory resistances was also well predicted ($\underline{r}$>0.98 for expiratory resistance, and $\underline{r}$>0.95 for inspiratory resistance).

As an introduction to his formal presentation, Dr. Bradley explained that the method for measuring pulmonary ventilation he was about to describe was still a laboratory tool. He added that he expected it to be developed, within about two years, into a system that would allow recording of pulmonary ventilation in divers. *A more detailed description of the system is available in Robertson, C. H., Jr., M. E. Bradley, L. M. Fraser and L. D. Homer. 1978. Computerized measurement of ventilation with four chest wall magnetometers. Naval Medical Research Institute, Report #NMRI 78-48, Hyperbaric Medicine and Physiology Department, Naval Medical Research Institute, Bethesda, Maryland, August, 1978.

Ventilation was measured with this magnetometer method in subjects during head-out immersion. This method accurately predicted tidal ventilation ($\underline{r}>0.98$) and vital capacity ($\underline{r}>0.94$).

It appears that this model and method is sufficiently accurate to allow it to be used as a resistanceless method of monitoring ventilation under a wide variety of tidal volumes, postures, and exercise states. It does not require a mouthpiece, does not alter dead space, does not impose a totally fixed body position, can be used during immersion, and can be used even when respiratory efforts are great. This system should be completely insensitive to changes in gas composition, density, and temperature. It may be particularly suited to studies of respiratory control mechanisms and respiratory mechanics in the diving environment, and may also provide a means of monitoring a diver's ventilation in other settings.

Discussion

In answer to a question about the stability of the system, Dr. Bradley said that for periods of up to an hour, drift had not been a problem. The apparatus had not yet been used for longer periods of time.

Of considerable practical interest was the question: what influence might metallic objects with which the working diver is almost always in contact have on the device? Dr. Bradley agreed that there was reason to expect the magnetometers to be sensitive to metallic objects, but added that the magnetometers had not yet been tested for that. He also acknowledged that if the magnetometer were to be used under a wet suit, some problems might arise from water moving in and out of the suit. He also agreed that there might be reason to look into the possible effects of oxygen's paramagnetism, as suggested by Mr. Gelfand. As for making the system useful for diver monitoring, work was in progress to condense it into a manageable package and to adapt it for real-time readout instead of the current method of deriving data from a magnetic tape.

Several comments were made to the effect that the system promised to be very useful and that it showed remarkable accuracy. This led to speculation about the origin of lung volume changes upon Valsalva's maneuver (straining) that could be detected with the method. Dr. Bradley suggested that these volume changes may have been due to displacement of blood out of the torso. Dr. Webb pointed out that a simple test of this hypothesis would be to perform Valsalva's maneuvers with and without arterial stasis applied to arms and legs by tourniquets.

AN OVERVIEW OF OPERATIONAL DIVER MONITORING TECHNIQUES

A. Slater

Let's briefly forget the limitations of present technology and look into the future at an "ideal" diver operational monitoring system. Physiological and environmental parameters would be measured by sensors that would, preferably, be built into the dive suit and equipment and would require no attention from the diver either in preparation or during the dive. Sensors that would have to be placed on the diver would require little time or skill for attachment and would be comfortable and not restrictive during the dive. The number of sensors used would be limited only by the need to keep preparation time reasonable.

Sensor signals would be preprocessed in a diver backpack to reduce noise and compress and encode the data for transmission to the surface.

The data link from diver to monitoring point would provide error-free transmission and would have a minimum of attachments to the dive system (cables, connectors, bulkhead penetrators) to facilitate easy installation and removal.

Once at the monitoring point, the data would be processed by a microcomputer. The computer algorithm would examine each parameter and confirm its validity by comparing it with predetermined limits and other related parameters. Further analysis would correlate parametric data to determine overall diver status.

Computer output would be very simple. A green light would indicate that the diver was within safe limits, and a red light would indicate the opposite. Having both lights out would indicate indecision caused by inconsistent data input or system failure.

Overall, the ideal system would be easy to attach, unobtrusive to the diver, have minimum physical and electrical interface with the rest of the dive system, present easy-to-interpret results, and have a low false-alarm rate.

And now, back to reality. How does present technology compare with the ideal? Sensors are clearly the weakest link in the system. No sensors exist in several critical areas. Physiological sensors are difficult to attach reliably to the diver, primarily because of motion and moisture effects. Environmental sensors don't require attachment to the diver and are therefore usually more reliable.

At least two viable data link options now exist. The classical multi-wire cable has given way to the simpler two-conductor multiplex cable, which can transmit multiple parameters by any of several encoding

schemes. The advantages are an ability to handle high data rates, insensitivity to electrical interference, and little inconvenience to the tethered diver. The disadvantages are the need for installation of cable, waterproof connectors, and bulkhead penetrators in the dive system and support vessels.

The second data link option is acoustic transmission. The primary advantage is elimination of connectors and wire from diver to monitoring point. This factor is critical in untethered operations and also greatly simplifies installation in existing dive systems where appropriate cables are not built into the system. Data rates of acoustic links are less than wire links but are more than sufficient for most physiological applications, including transmission of fast varying parameters such as the electrocardiogram. Acoustic problems such as multipath distortion and thermal layer shadowing effects are rare at the close ranges involved in physiological monitoring applications. Acoustic signals can also penetrate hyperbaric chamber walls as well as seawater. Thus, the same apparatus can be used to monitor diver status in deck decompression chambers pre- and postdive, by placing the receiving hydrophone against the outside chamber wall. The major disadvantage of acoustic telemetry is susceptibility to interference in some locations, primarily harbors close to heavy machinery, which can limit range to a few hundred feet.

Cigar-box-size microcomputers have become a practical reality in the last few years. These devices can be programmed for a variety of applications, such as extraction of heart rate from ECG's with muscle artifact, correlation of various inputs, and making simple decisions about incoming data that would otherwise have to be made by topside personnel.

Go-no-go displays, as described in the "ideal" system, have been around for years. For more sophisticated applications, digital and alphanumeric displays capable of displaying numbers and words are now available.

Finally, as an example of an existing acoustic monitoring system, the Emergency Care Research Institute has developed an acoustical telemetry system capable of simultaneous monitoring of up to nine physiological parameters. System components are shown in Fig. 1. Clinical ECG, skin temperatures, core temperature (by rectal probe or endoradiosound pill), respiration rate, and PO_2 can be monitored, in various combinations. The system has been used in over 1000 dives from the Carribbean to the Arctic since Sealab II. In the near future we will add a capability to measure heat flux for advanced thermal studies. We are working with Biomarine Industries to add PCO_2 monitoring capability to the system.

As an example of a computer-aided hard-wire system, the Institute for Environmental Medicine and Ecosystems, Inc. have developed a human performance monitoring system capable of measuring a wide range of

Fig. 1. System components.

psychomotor skills in divers. The hardware, which is common to all tests, is controlled by a computer programmed to control the equipment, execute the test sequence, collect data, perform statistical analyses, and print out results, all in real time.

Discussion

Dr. Thalmann took issue with Mr. Slater's statement that the lack of adequate sensors for certain physiological parameters is presently the greatest problem in diving monitoring. He held that lack of software is the major problem. Referring to his own presentation, he emphasized that even in the laboratory setting, which allowed high quality recording of a great number of physiological variables, highly trained persons were required to interpret the data. Even then, at the present state of the art we rarely can use the data to predict when a diver is headed for trouble. At best, it is sometimes possible to use the data retrospectively to suggest why a diver-subject became dyspneic during exertion at depth.

Dr. Vorosmarti elaborated on Dr. Thalmann's view that more laboratory work is necessary before meaningful interpretation of data is possible. He emphasized that a monitoring system, when taken out on the diving platform, should not require extensive data interpretation. The laboratory work must be done first to allow correlation of different physiological parameters with the physical condition of the diver. For the diving supervisor on the platform, this has to be translated into clear cut-off points.

Other discussants suggested that despite the need for more research, there are still a number of relatively simple processes that can be monitored and made use of. It was pointed out that everyone could probably agree on the interpretation of some data; if, for example, the oxygen in the breathing mask gets too low or the carbon dioxide too high, the diver is certain to get into trouble. A couple of speakers maintained, however, that recording carbon dioxide levels was really equipment monitoring rather than monitoring the diver's vital signs. Someone also asserted that monitoring the CO_2 in the diver's exhaled gas, rather than the gas supplied by the breathing apparatus, was a better method because it could reveal hypoventilation due to pathophysiological causes in a diver wearing a perfectly functioning piece of equipment.

Several discussants agreed that a reasonable and practical approach would be to use what little monitoring capability we have at present and prevent maybe a fraction of the accidents that occur. It was added that there is a very large gap between the level of understanding of those taking part in the Workshop and that typical on diving rigs and even in diving schools. The Chairman concluded that it rests with the participants of the Workshop and their colleagues to correct that discrepancy.

DATA PROCESSING AND PRESENTATION

William R. Braithwaite

First of all, let me warn you that the ability of computers to solve problems is highly overestimated. They are fast enough to do millions of operations per second, but they are frustratingly dumb. To be useful, a processor requires a very detailed and precise algorithm or programmed model to follow or it will fail. It does not have the human capacity to make value judgments or to interpret what you mean in context unless you instruct it precisely how to make those judgments. This means literally foreseeing every contingency and leaving instructions on how to handle each.

The processors themselves have undergone a remarkable metamorphosis in the past few years. They have been reduced in size from that of a bread truck to that of a loaf of bread and reduced in price from millions to hundreds of dollars. Even the well-known and very powerful PDP-11 minicomputer can be purchased "off-the-shelf" today, with a full complement of memory, power supplies, and external interfaces, in a briefcase-size package, for less than three thousand dollars. A less powerful microprocessor on a single chip half the size of a book of matches can be bought for seven dollars, but requires several hundred dollars worth of additions to make it able to perform useful functions.

Reliability of components has increased enormously, and we even have minicomputers today which can deliver 100% reliability by self-diagnosing hardware errors and automatically switching to redundant components.

Another important development for our purposes has been solid-state mass storage devices such as the magnetic bubble memory. This removes the need for a rotating disc memory, which would be the most power-hungry and vulnerable device in the diving environment. The bubble memory chip can be replaced to change the programming for any particular situation without the need of an on-site computer person. In the future, each diver could have his own memory chip which could provide base lines for his personal physiology, making a monitoring system much more sensitive and reliable.

Probably the most important point to be made is that these devices are general purpose and are adaptable to changes in function simply by changing the models or programmed instructions which they follow. For a few dollars, each device can be updated in the field without need for recall or replacement.

What will these processors be doing in our diver monitor systems? The first and most obvious function is analog to digital (A to D) conversion of the physiological signals into a meaningful sequence of numbers. Signal conditioning and data reduction through averaging, noise detection, rate picking, etc., can be done by analog circuits before A to D conversion or by digital processing after conversion. Perhaps more important is the capability to control the data acquisition process through means such as preamplifier gain control, self-calibration, and automatic zero suppression.

It is at this point that the most valuable contribution to diver safety can occur. Functioning in a manner similar to a flight recorder on an aircraft, the monitor system can record the raw data from each parameter being observed, including communications. The recording would be made on a removable, re-usable medium which could be used for analysis if complications develop during or after the dive. Such recordings could permit meaningful investigations into the causes of diving accidents.

The next stage of data processing is interpretation, and this is where the models are necessary. Using the model described earlier by Dr. Bradley, we can appropriately interpret the signals from a magnetometer array; but we also need a model which tells us what to do when the resulting ventilatory parameters vary during a dive. These models will embody the "intelligence" to evaluate present and predictable risk and provide decision aids at the dive site. It is also important to note that the memories of these processors will allow our models, like Dr. Webb's heat flux model, to take the whole history of a dive into account and to use an individual diver's base-line physiological parameters rather than a generalized set.

All of this processing need not take place in one processor. For example, the initial signal conditioning and A-D conversion could occur in a microprocessor in the diver's backpack and could present pertinent information to him while multiplexing the signals for transmission to the surface. At the surface, the recording and decision-making could be performed with further data reduction for display or alarm triggering.

The display itself is usually in the form of dials, digits, sounds, and lights, but should be capable of displaying more information than the current values of parameters. A free-form, TV-type display capable of plotting parameters against time is what I see being used in the near future. This allows an observer easily to interpret trends over time and to extrapolate or predict the diver's physiologic state. The processor could also use the trends to predict a future state and produce a message if that is appropriate: for example, "Warning, inspired CO_2 will exceed limit of 35 mmHg in 5 minutes at this level of activity."

Alternately, the complete dive history can be displayed at once, using a logarithmically compressed time scale, with individual values plotted for immediate past and averages with ranges plotted for increasing time periods as earlier parts of the dive are plotted. This would be most valuable for comparing sudden changes to a history of past performance.

The display is not only free form but can also be changed at will from displaying all parameters, to a detailed plot of one parameter, to a compressed time plot, etc. The processor could also select the display to use, depending on the most critical parameter or the one closest to "alarm" conditions.

The screen can also be used for text messages, which could include warnings, decompression tables, decision menus appropriate to the dive condition, etc. I would expect that more and more such decision aids would be added as experience and data were collected.

The classic computer alphanumeric/graphics terminal I am referring to here (which can be purchased for a few thousand dollars) is basically a television monitor with a keyboard attached. The TV monitor part has mechanical, power, and cooling requirements which may be limiting in some diving environments. Fortunately, a flat, solid-state display is now practical and will shortly be available as a replacement.

Alarm mechanisms can be quite sophisticated and will include several types. The simple, absolute limits would still be used but could be tuned to the individual diver. A second-level alarm would sense when a parameter went beyond a more sensitive limit for a specified period of time. I have already mentioned the third level, which warns of a trend that will exceed a limit in the future.

Each of these levels can be carried out in a multidimensional physiologic space which represents the interactions and relationships between the parameters being monitored as well as their individual values. This would produce a very sensitive mechanism with very little chance for false alarm, assuming that we can define or model that physiologic space well enough.

The alarm itself could be any one which will attract the attention of the appropriate person but, again borrowing from aviation studies, I would suggest that spoken messages backed up by appropriate informational displays would be best. Producing the spoken word is well within the capacity of today's microprocessors, with inexpensive voice synthesizers.

In summary, the processing and display technology is available today to produce a small, reliable, generalized diver monitor system. However, we have very few models available with which consistently to interpret physiological data for decision-making by the medically

unsophisticated dive supervisor. It is important that we begin monitoring divers and recording the data for accident investigations while we iteratively refine and test our models for interpretation.

Discussion

Dr. Braithwaite was of the opinion that one important property of a good monitoring system would be the ability to feed information back to the diver, who ultimately is in charge. This raised concern about whether that would distract from the task that he was meant to do. A contrasting view was held by Dr. Brady, and other discussants, who maintained that any feedback to the diver of a crucial nature would have to be maximally disturbing to stand a chance of being noted by him. This point was stressed by Dr. Egstrom, who cited experiments in which divers failed to note and respond to a red light in their diving masks when subjected to relatively moderate stress in the dive. The spoken word was suggested as probably the best means of communication to alert the diver.

Although it may be desirable to feed certain types of information back to the diver, it was noted that the situation in which he most needs it may very well be the one in which he is least capable of taking advantage of it (for instance, due to nitrogen narcosis, CO_2 accumulation, or hypothermia).

PHYSIOLOGICAL MONITORING OF THE ASTRONAUTS

Arnauld Nicogossian and James M. Waligora

The concept of continuous biomedical monitoring and telemetry was a relatively new one at the outset of the United States Space Program. Since then the technology of biotelemetry has made remarkable progress, with thousands of hours of long-distance continuous physiological data transmitted from outer space.

The main purpose of remote biomedical monitoring of space crews was to provide medical personnel with accurate real-time data with which to evaluate physiological status during such critical phases of the mission as launch, docking, extra-vehicular activity (EVA), and lunar exploration. The types of biomedical monitoring during space missions can be subdivided into three distinct categories:

1) The cabin environment provided cabin environmental parameters, in addition to the nominal operational bio-instrumentation data of heart rate, respiration rate, and body temperature.

2) The EVA configuration which, in addition to operational bio-instrumentation, allowed monitoring of oxygen consumption and acquisition of liquid-cooled garment (LCG) measurements, thus providing invaluable information on the metabolic cost of EVA.

3) Medical experimental data acquisition, especially Skylab orbital missions, provided Principal Investigators/Experimenters with near real-time information such as vectorcardiography, metabolic efficiency associated with exercise work loads, lower body negative pressure responses, electroencephalography, and so on.

Biomedical Monitoring

Operational bio-instrumentation was designed to be worn under flight clothing and consisted of an individually adjustable unit. This system underwent several modifications after the Mercury, Gemini, and early Apollo missions. In the Apollo Skylab configuration, the system consisted of electrocardiographic (ECG) electrodes applied in the CM5 configuration, an impedance pneumograph (ZPN), a body temperature signal conditioner and probe, a DC-to-DC converter, and interconnecting cables (1). A brief description of these components follows:

1) The ECG signal conditioner and electrodes were designed to provide in-flight measurements of cardiac electrical activity and to develop a signal wave response ranging between 0 - 5 volts

peak-to-peak. This unit was provided with special adjustments for pre-flight calibration.

2) The ZPN signal conditioner and electrodes were designed for measurements of transthoracic impedance, with a low level current response at 50 kHz. A pair of electrodes, with signal response ranging from 0 to 5 volts peak-to-peak, provided dynamic data on respiration rate.

3) The body temperature probe and the signal conditioner produced a response in the 0-to-5 VDC output, corresponding to temperatures of 85° to 115°F.

Monitoring of the Extra-Vehicular Activity

Up to the time of the Apollo 14 space missions all crew members were continuously monitored while in flight. Beginning with Apollo 14, biomedical data were obtained on a continuous basis for at least one crew member. Usually during lunar surface activity, both crew members were closely monitored, and biomedical data were obtained on all astronauts during the launch and landing phases of the mission.

Before the first Apollo EVA, there was general concern over the possibility that high metabolic rates might preclude effective operational performance. This concern was based on data obtained during previous Gemini EVA which showed metabolic rates in excess of predicted values. Early Gemini information was essentially derived from the heart rate data. This concern was justified by the fact that the useful life of a portable life-support system (PLSS) on the lunar surface depended on the usage rate of consumables, i.e., oxygen, sublimator water supply, and carbon dioxide absorber. Three independent methods based on common laboratory procedures were evaluated and incorporated into the metabolic rate activity assessment. These laboratory procedures consisted of: 1) heart rate; 2) oxygen consumption; and 3) heat removed from the crewmen by the LCG.

Each of these indicators of work load was extensively studied for correlation with metabolic activity level, and it was found that though useful data could be obtained, they tended to lack accuracy when used alone.

Heart Rate Method

Because heart rate is so dependent upon total physiological and psychological stress, it may not be an accurate estimate of metabolic rate. Heart rate measurement is, however, the only available technique with a time-lag short enough to allow a near real-time estimate of energy expenditure. In addition to the known intervening inaccuracies, i.e.,psychogenic factors, heat storage, and fatigue, three unique problems were encountered during the space mission: 1) calibration curve

inaccuracies; 2) crew member cardiovascular deconditioning; and techniques used to determine heart rate (2).

To compensate for these inaccuracies, calibration curves were adjusted individually, preflight, during exercise stress testing, for each astronaut. To account for the effects of the in-flight deconditioning, a sleep ECG was obtained on each astronaut. In the long range, it was found that errors of up to 80% did occur in some cases and it was recommended that heart rate alone should not be used as an indicator of metabolic rates in space flights. Heart rates and calculated metabolic activity for the Apollo 15 Commander are shown in the figure below.

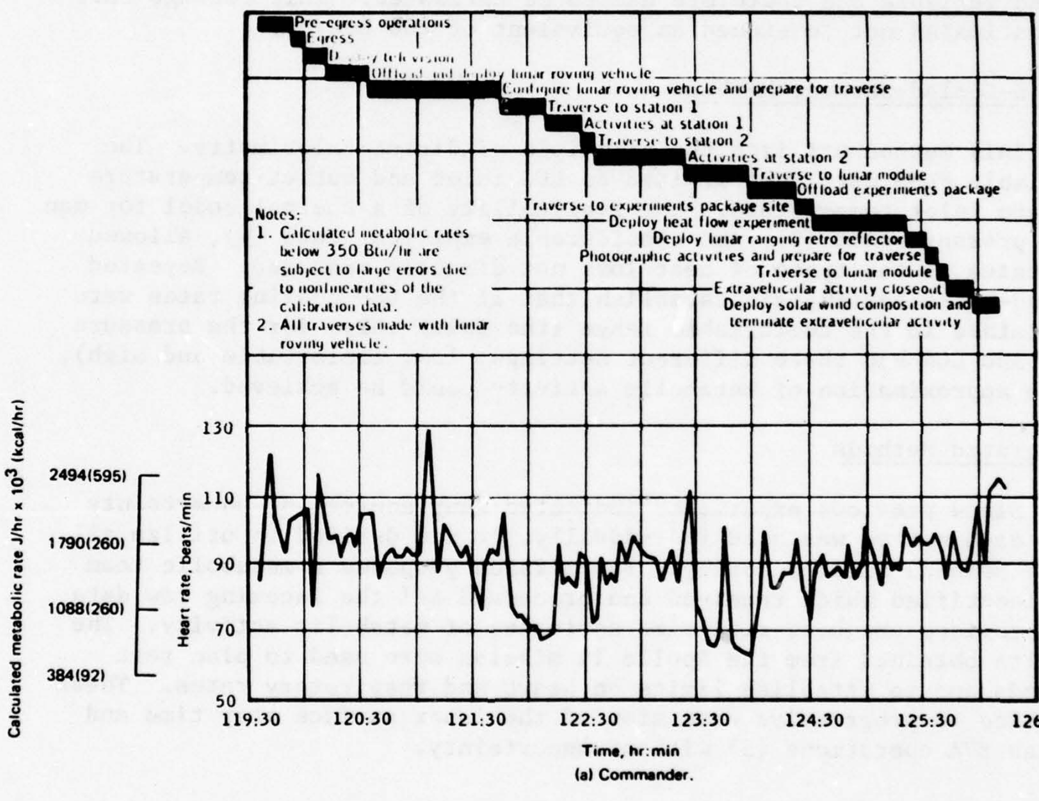

Fig. 1. Heart rates and calculated metabolic rates of the Apollo 15 Commander during EVA-1.

Oxygen Method

This method involved the measurement of the PLSS oxygen bottle pressure decay to estimate oxygen consumption and thus metabolic rates. The bottle pressure was telemetered from each EVA crewman and displayed in real-time. However, the respiratory quotient (RQ) was estimated and not directly measured, which presented a special problem when assessing the energy expenditure accurately. The second problem associated with this method consisted of a random noise error in telemetered data. To minimize this error, the metabolic data were not computed until a significant drop occurred in bottle pressure, precluding adequate information on the status of consumables and crew member condition at lower metabolic rates. Also, the pressure-suit oxygen leakage rate proved variable and therefore had to be estimated. This leakage rate was estimated not to exceed an equivalent of 200 Btu/hr.

Liquid-Cooled-Garment Method

This method utilized the principle of direct calorimetry. The available PLSS data were limited to LCG inlet and outlet temperature and gas inlet temperature. The availability of a thermal model for man in a pressure suit (3), and considerable empirical data (4), allowed estimates of the types of heat loss not directly measured. Repeated ground-based testing did establish that if the LCG cooling rates were maintained in the comfortable range (the inlet valve for the pressure suit and LCG had three different settings: low, comfortable and high), close approximation of metabolic activity could be achieved.

Integrated Methods

Since previous experience indicated many sources of uncertainty when each method was used individually, it was decided to utilize all three methods simultaneously. For mission purposes a metabolic team was identified which received and processed all the incoming raw data and provided the best real-time estimates of metabolic activity. The results obtained from the Apollo 11 mission were used to plan rest periods and to establish limits on heart and respiratory rates. These data led to progressive extension of the lunar surface stay time and Skylab EVA operations (5) without uncertainty.

CONCLUSIONS

During the actual EVA, the flight surgeon had to be ready to decide whether it was advisable to continue an activity and to aid in planning for deviations in the mission plan. For these reasons it was required that data on both the cumulative and the peak energy demands on a given crew member performing EVA be available in near real-time. The

integration of all three methods provided this type of data. In retrospect, it can be said that the use of this type of data during space missions prevented the astronauts from exceeding pre-set heart-rate and respiratory-rate limits and assured that acceptable tolerance limits were maintained.

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Discussion

The discussion after this presentation centered around the level of sophistication required by the persons evaluating the data obtained during monitoring. Dr. Nicogossian felt that physiological monitoring and interpretation were no longer an art but a science. He added, however, that this work takes a fair amount of training and awareness on the part of those who will decide when to stop, when to go, when to rest. As for the background required of these persons, it was recognized that the space effort is unique in that it can draw on teams of highly trained specialists in physiological monitoring and clinical evaluation. Nonetheless, it was emphasized that the diving community should reject the idea of forever being saddled with diving supervisors insufficiently trained in diving physiology and diving medicine.

Redundancy, valuable during monitoring of the astronauts, is equally important in diving because it compensates for different types of weaknesses in different types of monitoring and improves the likelihood of discovering false readings.

SPEECH AND ITS POTENTIAL FOR STRESS MONITORING

Arthur J. Bachrach

Introduction and Apologia

When Dr. Lundgren invited me to participate in this Workshop on Diver Monitoring, particularly to discuss the possibilities of monitoring speech for stress indicators, we agreed that I was not an expert in the area of speech (an easy agreement to reach), but that I could review the field from the general standpoint of what has been accomplished and from my own special interest in verbal behavior and style. I am indeed not a speech scientist, and most of the material I have read for this working paper comes, necessarily, from linguists, speech pathologists, computer engineers, psychoacousticians, and professionals within the area of security and crime prevention. The very nature of this widely representative group bespeaks the strong interest in areas such as vocal stress analysis (for varying purposes) and the exquisite complexity of the area, drawing as it does from so many disciplines. In discussing some of this work I have, undoubtedly, done injury to some of these writers' thoughts and findings. I have tried to keep these to a minimum to the best of my integrative ability, and I apologize for lacunae and misinterpretations. Nevertheless, this is, in every sense of the word, a working paper to acquaint the Workshop group of experts in the diving area with a potential methodology. As a working paper, it is preliminary, exploratory, and will eventually be modified and enlarged, as is appropriate to a complex and highly technical area.

Background

In the search for effective ways of monitoring diver stress, the possibility of using voice has much to recommend it. Vocal communication is, in all probability, the most frequent and, perhaps at times, the only communication between a diver at depth and topside personnel. The situation regarding research on vocal stress in diving seems to be reflected in Wathen-Dunn's (1972) observation at a workshop on processing helium speech:

> I think there are three aspects of the speech signal that are important to preserve in a communications system. The first, of course, is intelligibility, but a second is talker identity, and a third is what I call the emotional content of the speech. These convey what was said, who said it and how it was said. In helium speech we seem to be happy if we can preserve intelligibility, and we haven't worried about the other aspects. (p. 64)

Wathen-Dunn's observation that researchers in the field "haven't worried" about aspects other than intelligibility is borne out by a search of the undersea research literature (Shilling and Werts 1973; Werts and Shilling 1975, 1977; Shilling, Werts, and Schandelmeier 1976), as well as by my individual queries (Hollien 1978, personal communication). These searches showed that there have, indeed, been no reports published in the open literature that made a voice stress analysis of diver speech. Much excellent work has been reported in the important area of diver speech intelligibility, and the very successes attendant upon helium speech research and the engineering of unscramblers has, in a real sense, rendered helium speech intelligibility a completed phase of speech research underwater.

Thus, for the purposes of the present report, the field of intelligibility of diver speech will not be covered. Rather, we will concentrate on Wathen-Dunn's other two categories: talker identity (to be referred to by its more common term, speaker recognition) and the emotional aspects of speech. These areas have been subjects of considerable research, although not in the context of diving, and I believe it would be fruitful to consider salient findings from these areas to assess the potential for elements in diver speech that may signal distress.

The words emotion and stress have superfluous meanings. For the purposes of this paper, I am defining stress as a nonspecific stimulation, not always negative, of body imbalance, whch evokes action for restoration of equilibrium. Each individual perceives the stressor in a manner that is different from others and subjectively responds to his own perceptions of the stressor. Emotion *is defined as body imbalance* subjectively experienced in strong feeling, which may be reflected in vocal transmission of a message. Our interest, of course, would be in detecting stress potentially dangerous to the diver.

Speaker Recognition

Style (which I shall roughly define as individual variation) is a learned response by listener as well as speaker, in a manner of speaking (no pun intended). We learn to recognize individual speakers over the telephone, or to recognize specific singers without visual cues. Hecker (1971), in a monograph on speech recognition, observes that there are three modes of speaker recognition: the human listener; visual displays of speech (such as spectrograms); and recognition by machine. Of the three, the first - the human listener - still stands as the best, although advances in visual display and machine recognition have been made. Hecker (1971) notes there is indeed variability in individual speakers from sample to sample: "The same speaker rarely utters a given word twice in exactly the same way, even when the utterances are produced in succession...." (p. 4). Although intraspeaker variability occurs, there is still sufficient difference between and among speakers to identify individual speakers, and any variations that may occur in an individual himself can be offset.

This, incidentally, illuminates one of the problems of speech research: Often it is stated that trained speakers and trained listeners are important to the analysis of relevant parameters. Ideally, a diver in a speech sample must be motivated to articulate precisely, often a difficult achievement, given operational considerations. Diver communications, by virtue of such elements as masks and audio equipment, are distorted, and helium conditions further distort speech. If speech monitoring is to be effective, it must analyze running (connected) speech efficiently, and it must accept speech samples under "real-world" conditions of work and hazard, where a diver is unlikely to purse his lips precisely. I do not mean to sound facetious in this -- it is a real research/operational problem.

There have been many studies on the perceptual basis of speaker recognition, studies aimed at identifying parameters that offer cues to speaker identity. As Hecker (1971) notes, "Underlying most studies of this kind is the assumption that a listener makes use of only a small number of perceptual parameters in discriminating between voices and in identifying familiar speakers" (Hecker 1971, p. 37).

Machine Recognition

The machine analysis of prosodic features of speech, such as intonation, timing, and stress (linguistic features rather than acoustic), has developed extensively, illustrated by work such as that of Lea, Medress, and Skinner (1975); Cheung, Holden, and Minifie (1977); and Ainsworth (1973). These papers are but a fraction of the large body of literature in speech recognition by machine and are offered as representative samples of such an approach. In all of the work, promising leads toward machine (computer, spectrogram) recognition of spoken sounds have been seen, but we are still not able to rely on these techniques.

In sum, the best identifier of human speech currently appears to be the human listener. The cues used for such identification are largely linguistic and include, in the words of Bunge (1975), "the sound of his voice, characterized by spectral components, the loudness and pitch as well as their temporal variations [and] other features, like the speaking speed rate, the length of pauses and the length of the stationary sound." Judgments by the human listener of slow/fast tempo, roughness versus smoothness, open qualities versus rasp, in addition to pitch and intonation, form major sources of speaker recognition. The potential for stress monitoring would be in the recognition of speaker characteristics and deviations from this characteristic speaking style.

The Emotional Aspects of Speech

Most of the interest in verbal behavior among psychologists and other students of human behavior has been in the content of speech

rather than its structural aspects. The verbal aspect of speech dealing with message transmission through content is, perforce, accompanied by the vocal aspect, the carrier of the spoken message. Separating these two elements to a degree is artificial, but it can be valuable in an analysis of spoken messages. A further element is that of syntax, the structure of the message. An illustration of these elements is offered by Dreher and Bachrach (1969). Analyzing an example of "psychotic" speech, these authors took a long passage from a hospitalized patient (Cameron 1947). The patient, when asked by his therapist, "Why are you in the hospital?" responded "I'm a cut donator, donated by double sacrifice." The bizarre content persists in this manner throughout the interview, but Dreher and Bachrach indicate that throughout the passage and not just in this first sentence the syntax is perfect: "Syntactically, this is structurally identical to a sentence such as, 'I'm an accident victim, run over by a truck'" (Dreher and Bachrach 1969, p. 927).

Dreher and Bachrach (1969) present noncontent analysis of spoken passages from a standpoint of power spectral density analysis (vocal rhythm) in which the periodic components of delivery are compared for John F. Kennedy's Inaugural Address and Cuban Crisis Speech (Fig. 1).

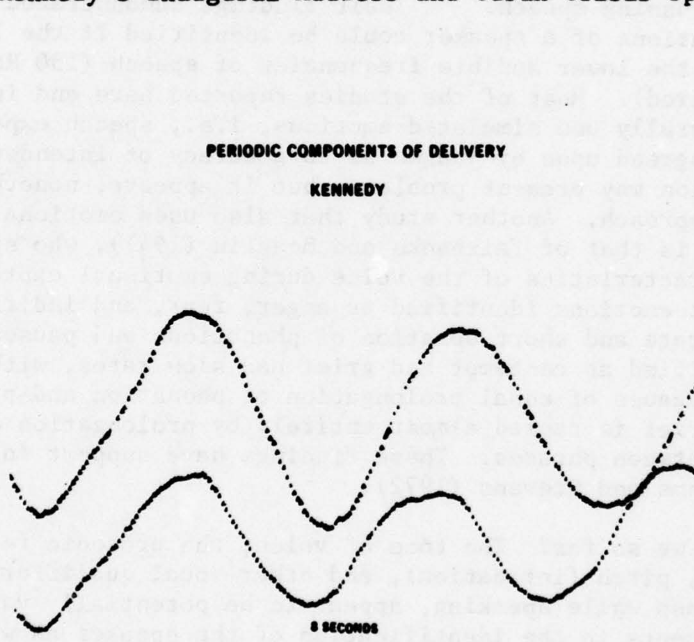

Fig. 1. Top trace is Inaugural Address; bottom trace represents Cuban Crisis speech (from Dreher and Bachrach 1969).

Bachrach and Dreher state that "a speaker's periods are also a mirror of his systemic rhythms" (p. 932), and, despite the content differences between the two speeches, the vocal rhythm is consistent in both.

Other investigators over the years have studied noncontent aspects of speech to analyze emotional factors. For example, in a series of experiments Starkweather (1956) filtered out content from spoken messages by using a bandpass filter with samples of speech attenuated above 300 Hz and found that emotional qualities of speech could be determined from the lower portions of the spectrum with good reliability (by judges). Similar findings were reported by Alpert, Kurtzberg, and Friedhoff (1963).

A recent study by Ross, Duffy, Cooker, and Sergeant (1973) addressed the question of whether lower audible frequencies contained enough prosodic features of voice (intonation [pitch] contours, syllable and word stress [intensity duration], and the relative duration [time] of the utterance [phonemes, morphemes, words and phrases]). As Ross and his co-workers (1973) observed, "These rhythmic and temporal features of the speech wave are considered to be 'fundamental in the perception of running speech.' " Their findings demonstrated that the emotional intentions of a speaker could be identified if the listener only perceived the lower audible frequencies of speech (150 Hz low-pass frequency filtered). Most of the studies reported here and in the literature generally use simulated emotions, i.e., speech expressed by actors and agreed upon by judges as to accuracy of intended emotions. Such a simulation may present problems, but it appears, nonetheless, a successful approach. Another study that also uses emotional simulation by actors is that of Fairbanks and Hoaglin (1941), who studied the durational characteristics of the voice during emotional expression. They found that emotions identified as anger, fear, and indifference present rapid rate and short duration of phonations and pauses. Emotions identified as contempt and grief had slow rates, with contempt being slower because of equal prolongation of phonation and pause; the slow rate of grief is caused almost entirely by prolongation of pauses, particularly between phrases. These findings have support in a recent paper by Williams and Stevens (1972).

Where are we so far? The tone of voice, the prosodic features of time, loudness, pitch (intonation), and other vocal qualifiers, such as openness and rasp while speaking, appear to be potentially valuable linguistic elements in the identification of the speaker as well as the speaker's emotional state. It is patent that such emotional expressions are learned. The differentiation of contempt and grief, for example, is not entirely either an acoustic or a physiological event. People learn to express emotions, and the very fact of speech manipulation by stress and intonation changes the character of the message for the listener.

For purposes of monitoring speech, the emotional aspects of spoken messages are obviously the most important. Williams and Stevens (1972) suggest that the fundamental frequency of the speech signal versus time is "the clearest indication of the emotional state of the talker." The fundamental frequency is the rate of vibration of the vocal folds during speech. An increase in the fundamental frequency generally indicates certain physiological adjustments (Huttar 1968) such as an increase in subglottal pressure (Ladefoged and McKinney 1963). An increase in intensity may be an indication of an increase in subglottal pressure (Ladefoged and McKinney 1963) and/or an increase in glottal efficiency (Isshiki 1964). Generally, an increase in laryngeal tension and muscular activity brings about these changes in laryngeal configuration. Increased activity of various respiratory muscles causes an increase in subglottal pressure (Ladefoged 1962). The increases in muscular activity are caused by the increased muscle tension throughout the body, which appears to be a concomitant of emotion (Lindsley 1951, cited by Huttar 1968, p. 486).

In another paper Williams and Stevens (1969) make the point:

> It appears as though the fundamental frequency contour for a breath group generated in a normal manner without marked emotion is characterized by smooth, slow, and continuous changes in the fundamental frequency as a function of time, the changes occurring in syllables upon which emphasis or linguistic stress is to be placed. When the speaker is undergoing emotional stress the contour exhibits greater excursions or fluctuations than it does when the talker is speaking in a neutral situation. (p. 1372)

These authors refer to "breath groups," indicating a relationship between speaking, emotion, and respiration. Indeed, they cite Lindsley (1951) as noting that "....respiration is frequently a sensitive indicator in certain emotional situations," and note that an increased respiration rate would presumably result in an increased subglottal pressure during speech (and a higher fundamental frequency during vocalization). A similar increased respiration rate can be found in scuba divers experiencing stress and panic, which Bachrach and Egstrom (1976) refer to as <u>hyperventilation</u> or, more properly, <u>tachypnea</u>. Williams and Stevens (1969) note that the increase in respiration rate would also lead to shorter durations of speech during the period between breaths and a resulting change in temporal speech patterns, related to the timed elements discussed previously.

Thus, for diving, the monitoring of spoken passages can be related to changes in respiration rate as well as to other physiological events. Respiration rate is also a readily available datum in diver monitoring.

All of these events we have described in speech occur at surface pressure, in persons breathing normoxic air. What can happen to normal speech production in the diving environments (where divers are subject to the effects of helmets, masks, pressure, air and exotic breathing gases) and the water environment, has been researched by authorities such as Fant and Sonesson (1964), who studied speech at high-pressure ambient air as well as in a compressed air environment (1967); Fant, Lindquist, Sonesson, and Hollien (1971), who investigated speech changes in air and He-O_2 pressure environments; Hollien and Doherty (1970), who analyzed speech intelligibility changes as a function of diving masks and mouthcups; and Ackerman and Maitland (1974), who developed a set of tables of the relative speed of sound in various diving gas mixtures. These works are representative of a body of data that has investigated the major impact of such factors on the musculature involving speech production.

Thus, we return to the original observation of Wathen-Dunn (1972): the emphasis in underwater speech research still is placed on intelligibility and speech distortion because of these many environmental and equipment factors. What is hopeful for those of us who are interested in speech as a potential for stress monitoring in divers is that there is a body of data illuminating speaker recognition and normal speech in air and its measurement, as well as on the effects of apparatus and environment. Coupling these may provide the impetus for directing research toward speech monitoring of diving conditions that is not aimed toward distortion alone, but uses speaker recognition, style characteristics of speakers, and stress indexes of emotional changes in speech production to detect early changes in diver status.

Vocal Stress Analysis: Current Approaches

In recent years a spate of stress analyzers has hit the market, professing to provide an analysis of voice that can detect emotional stress. The application of these, by and large, has been in the lie-detection area. A controversy has arisen about two questions: 1) Do they really detect stress and if so, how? and 2) If they work, are they illegal invasions of privacy? (The manufacturers often claim they can be used over the phone.) The most recent entry in the stress-analysis-machine group is a device called the HS-2 model from Hagoth, which no one in vocal stress analysis seems to take seriously. The HS-2 appears to have no valid proof of success other than the claims made by the corporation that markets it (largely through advertisement in airline magazines and similar trade journals). For example, Hagoth claims in ads that you can tell if someone is telling the truth over the phone, by means of a bank of green and red flashing lights. There has been no published confirmation of any of the claims to detect stress in this manner.

Other devices on the market are the Mark II Voice Analyzer developed by Law Enforcement Associates, which gives a numerical readout of voice changes; the Mark IX from Communications Control Corporation, which gives a similar digital readout; and the most widely used, the Psychological Stress Evaluator (PSE) from Dektor Counterintelligence and Security. This PSE provides a visual spectrogram from which stress levels are inferred from frequency changes. There are controversies surrounding the use of the PSE because there have been so few published research papers assessing it as a stress analyzer (most have been unpublished presentations at meetings); those papers that have reached publication have not been in scientific research journals, and the results have been varied as well.

In an annotated bibliography prepared for the 1977 seminar of the International Society for Stress Analysis (ISSA), Borgen searched 15 papers reporting on use of the PSE in nondeception situations. Several of these suggested that stress could be detected by the PSE, but most reports indicated that the PSE worked only under acute or high stress conditions (Borgen and Goodman 1976; Reeves 1976; Rockwell and Hodgson 1976). Their results were similar to those in a low-risk lie situation reported by McGlone, Petrie, and Frye (1974), in which a graphic level recorder for relative intensity was used to perform a spectrographic analysis for measures of frequency and duration and the PSE-1 was used for pattern matching. Neither technique proved successful above chance expectation. An interesting study in the light of our previous discussions about respiration and stress is that reported by Smith (1974), who used the PSE and found that "the audio stress response was appreciably reduced if hyperventilation was present."

Brockway, Plummer, and Lowe (1976) published a study in which obstetrical patients who were interviewed by nurses showed the same level of anxiety when measured vocally by the PSE as when measured by a paper-and-pencil test of self-reported anxiety.

The marketers of the PSE, Dektor Counterintelligence and Security, report an unpublished study by Older and Jenney, which was accomplished for NASA to test the effectiveness of the PSE in evaluating two NASA missions. Statistically significant relationships were found in the visual inspection and rating of spectrograms, but again, it appears that the PSE worked under conditions (definitely documented) of high stress and, according to the full report, its predictive value was not sufficient to warrant its use in assessing psychological stress in crew members. In view of the high-stress assessments, it seems that what is really needed is an "early warning" system that can inform the observer of impending changes in a crew member, patient, diver, or other operator under stress-evoking conditions--changes that presage serious trouble.

John Brady (personal communication, 1978) reports the use of the PSE during a pilot study involving 6 divers on a 380-foot helium-oxygen

saturation dive. His definition of stress in this dive was a physical work stress ranging from zero to 50 to 100 to 150 watts on a bicycle ergometer. Using this definition of stress, Brady had the divers' vocalizations analyzed by Dektor-trained personnel at the Patuxent River U. S. Naval Air Station. The PSE did not discriminate stress and the results were only at the chance level. That this study did not reveal any stress through the PSE could be a result of a number of factors, including the definition of stress, i.e., perhaps the physical stress was not entirely equivalent to emotional stress. Other factors involved may have been the distortion of the mask, the breathing mixture, and the fidelity of the communication system. Whatever the reasons, the PSE did not discriminate stress under circumstances of a standard dive.

Perhaps the major problem concerning the use of the stress analyzers is the stated mechanism by which they are supposed to work, the detection of suppressed microtremor, an 8- to 12-Hz low-frequency response presumed to originate in the central nervous system. Lambert (1974), in a review of the use of the PSE, reports that the manufacturer (Dektor) states, "The functional indicator of stress sensed by the PSE appears to be controlled by the central nervous system while those sensed by the polygraph are controlled by the autonomic nervous system," with an ANS holdover not found in the immediate recovery of the CNS after removal of the stress stimulus (Lambert 1974, p. 335). Comparisons with the polygraph have been made by several investigators, including Kubis (1973), who reported a simulated theft experiment in which polygraphic assessments were compared with voice analysis techniques and the latter were found nondiscriminating, although the polygraph itself performed little better than chance.*

To return to the crucial question of microtremor. The manufacturers cite physiological tremor as a basis for the analysis, properly quoting such authorities as Lippold (1971) to demonstrate that a physiological tremor ranging from 8 to 12 Hz exists and has been measured. This range of normal test tremor (Brumlik and Yap 1970) has been used as a valuable measure of finger tremor in studies of the high pressure nervous syndrome in deep dives (Bachrach and Bennett 1973), but there appears to be no conclusive evidence that such a microtremor exists in the vocal apparatus and the transfer from normal physiological tremor to vocal cords appears unwarranted.

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*The use of the polygraph as a standard for comparison in itself is somewhat specious. Rice (1978) cites a recent Justice Department report in which he quotes, "a conspicuous lack of reliable data" on the machine and states that the figures of 98% or 99% accuracy cited by polygraph examiners are "unsubstantiated."

Although the statement is made frequently in discussions of the stress evaluator that the central nervous system is the source of the vocal tract tremor, only one study purporting to demonstrate this appears in the literature, a study by Inbar and Eden (1976) in which EMG correlates of the Psychological Stress Evaluator were sought. These authors state that their experiments confirmed the CNS source of the microtremor, but their techniques of analysis are less than optimal. The EMG correlates were derived from two methods: 1) by transcutaneous stimulation of the vocal tract muscles by external surface electrodes "to verify the ability of muscle tension changes to generate correlated voice tremor"; and 2) by the use of a throat microphone to detect "tremor type vibrations in the pitch waveform." Neither of these methods appears to be optimal in determining electromyographic correlates.

Papcun (1974) discusses physiological tremor and in an abstract of a presentation at the Acoustical Society of America notes that the "functioning of a device to measure stress from speech depends on three propositions.... (1) the oscillation occurs in the muscles of the vocal apparatus during speech; (2) the oscillation is manifest in the acoustic signal of the speech; (3) the oscillation is attenuated or modified by "psychological stress," and he adds a fourth, "the oscillation and changes in it can be detected, displayed, and evaluated." The abstract also raises questions about the possible linguistic significance of physiological tremor. Although this presentation has never been published, the answers given at the meeting were generally in the negative. Physiological tremor does look like a promising expression of a stress response, but it is clear that no conclusive evidence exists for the explanation that suppression of vocal cord tremor is a stress index in voice stress analysis.

Summary

There has been considerable interest in the possibility of using voice as a means of detecting stress; to this day the promising aspects of speaker recognition, fundamental to a stress analysis, appear to be linguistic. These include pitch, intonation, tempo, and voice quality (rasp/openness, for example). The search for acoustic correlates for these linguistic perceptual parameters continues and the research in machine recognition, e.g., computer pattern recognition, visual analyses by spectrograms continues as well. Despite considerable interest and activity, currently available commercial voice stress analysers, based generally on frequency analysis, do not appear to be effective except in conditions of high stress; therefore, as early warning systems for stress, which would be most desirable, they have little value. At the present time, cost, space, and technology make it necessary to say that we have not yet arrived at a truly reliable automated means of speaker recognition or vocal stress analysis under normal conditions of air at surface pressure. Compound these problems with pressure, oral-nasal masks, respiratory loading, immersion, helmets--to name a few confounding variables in diving--and the problems grow exponentially.

Vocal stress analysis has a great potential and perhaps the developing technologies (such as microprocessors) will eventually allow us to solve existing problems and achieve real-time analysis of connected (running) speech as a dive monitor.

The author thanks Mary M. Matzen and Doris N. Auer for their assistance in the preparation of this manuscript.

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Discussion

Unforeseen circumstances kept Dr. Bachrach from attending the meeting, but he kindly submitted the manuscript for his planned presentation so that the Workshop participants could read it. Dr. Bachrach's cautious view with regard to the present usefulness of voice analysis for stress estimation was not seriously challenged. In addition, several discussants pointed out the technical difficulties in adaptation of voice analysis to underwater use, even if it is eventually made to work at one atmosphere. Such difficulties, it was felt, would be caused by high pressure and helium effects on speech. This brought up other aspects of speech communication and Mr. Gelfand offered some information on how to improve the intelligibility of speech at depth. He referred to speech monitoring tests conducted at the Institute for Environmental Medicine of the University of Pennsylvania, in which the intelligibility of unprocessed speech changed hardly at all from 200 to 1600 fsw, whereas other measurements have indicated that intelligibility deteriorates rapidly in the range of 200 to 800 fsw. He suggested that the problem in the latter case was that unsuitable microphones (ordinary communication-type microphones or high-fidelity microphones of conventional design) had been used; the increased gas density had reduced the frequency response of these microphones at the same time that both helium and pressure raised the higher frequency content of the speech. In this way when helium speech unscramblers are used their electronic capabilities cannot be used to full advantage. In the experiments in which Mr. Gelfand had been involved, better intelligibility of speech was obtained because condensor microphones were used with a frequency response that was flat far beyond the range of ordinary microphones.

DISCUSSION OF GENERAL TOPICS

Voice Communication in General

There was general agreement that voice communication is of great value for monitoring the diver's well-being. Also seen as important was the fact that speech communication allows the diving supervisor to control the diver's behavior to enhance his safety. In addition, sound communication may allow the diver's breathing frequency to be monitored.

Two major reservations about the usefulness of speech monitoring were discussed. Dr. Ackles made the point that in reality very little is usually said between diver and supervisor. Conversation is mostly limited to short technical information composed for intelligibility in jargon form, such as (supervisor): "ok, red," and (diver): "ok, yellow." Obviously this would not convey any subtleties with regard to the diver's level of dyspnea or anxiety. In this context Cdr. Duffy suggested that divers as well as supervisors should be trained to talk, and Dr. Bennett proposed that frequency of contact should be regulated or standardized, possibly to once every minute.

It was suggested that one reason why the diver might be unwilling to speak is that he is often too uncomfortable to talk; the face mask may exert too much pressure on the jaw or he may be short of breath. This could be compensated for if the diving supervisor was trained to ask the diver the proper questions at regular intervals. The diver's answers could then be short without reducing information. This suggestion gave rise to another reservation, however. It is well known that the diver sometimes misinforms the diving supervisor about his condition in a difficult situation. This may happen for any one of several reasons: the diver has the old macho attitude that a good diver can do anything, or he is unaware of his condition (due to N_2 narcosis, hypercapnia, hypothermia or hypoxia). It was strongly recommended that the communication between diver and tender be recorded on tape whenever possible, and kept until the dive has been brought to completion.

Visual Monitoring

The value of visual monitoring of the diver was brought up repeatedly both by keynote speakers and discussants. Dr. Barnard stressed that the fundamental vital sign recorded by visual monitoring--movement--has to be evaluated in relation to the operational situation: is the diver doing the expected, are his movements purposeful, coordinated, and as fast as expected? One speaker suggested that lack of training in monitoring may have contributed to the passivity shown by the monitors who watched one much publicized diving accident develop on the TV screen they were watching.

It was realized that visual monitoring has its limitations, for instance in turbid water or when the diver ranges over large distances. In these cases the diving buddy system is the time-honored method.

Training and Other Aspects of General Application

Several Workshop participants emphasized that various types of monitoring stood the chance of becoming more useful if the data could be related to better reference frames. The diver and the tender should be trained together much more often than is now the case. For instance, a tender monitoring the video or listening to the communication line who knows his diver well would be in a much better position to recognize when the diver's performance deteriorates (much in the same way an athletic coach can spot minor flaws in athletes and take corrective action before serious problems develop).

The training of divers and tenders should include programmed exposures to experiences that may cause particular problems or be indicative of problems for the working diver. Specifically, it was mentioned that dive team members needed exposure to cold water and to exhaustive work in simulated dives to be familiar with what hypothermia, fatigue, and shortness of breath at depth mean.

It was pointed out that to accomplish these goals will require much more of a team approach in dive crew training than has been employed to date.

Several speakers emphasized the problems of evaluating physiological parameters because of individual variability. The suggestion was made that a diver's response to various stresses should be monitored under controlled conditions and used for reference purposes during in-sea diving. Dr. Braithwaite pointed out that such information may be stored on individual memory chips that can be brought up to date at regular intervals. This chip would be plugged into the computer, which would then be able to indicate to the dive supervisor whether, for instance, the heart rate, minute ventilation, and rate of cooling recorded in an ongoing dive was commensurate with the particular diver's usual values. It was stressed that as far as data treatment technology is concerned, monitoring these variables is perfectly within the possibilities of today's state of the art.

Equipment Monitoring

Dr. Spaur addressed the general need for monitoring the diver's equipment to ensure that it is functioning properly before we concern ourselves with monitoring the diver's physiology. Other speakers agreed that monitoring the diver's vital signs is no substitute for properly functioning equipment, or for a good dive plan and adequate supervision. But it was also stressed that situations have actually occurred in which

the diver was not functioning normally, despite perfectly functioning gear. Furthermore, proper design of the monitoring system may accommodate both equipment monitoring and physiological monitoring. For instance, if one placed the carbon dioxide sensor in the mouth piece or breathing mask rather than in the line supplying breathing gas, readings during expiration would indicate whether the diver was ventilating his lungs sufficiently in relation to metabolic carbon dioxide production.

EPILOGUE AND CONCLUSIONS

Claes E. G. Lundgren

At the beginnning of this Workshop several key questions were asked:

What physiological parameters can be monitored to provide information relevant to the diver's safety?

What is the range of normal, and what is the risk of false signals?

Are the monitoring methods simple and reliable enough for operational diving?

Are we of the medical community prepared to interpret and act in real time on the monitoring signals?

Can the criteria for evaluation be used for automated data evaluation, allowing the dive supervisor and/or the diver without a medical background to make practical use of physiological monitoring?

What use can be made of physiological monitoring for retrospective accident analysis?

The National Plan,* published in 1976, had rather firm answers to some of these questions in its chapter on monitoring techniques. This work recommended as most important that pressure, time and voice be recorded, and with regard to diver safety monitoring (to be performed in high-risk diving situations) it recommended that: "1) heart-rate, which reveals the diver's response to stress in general and exertion in particular; 2) respiration rate, which provides early warning signs of overbreathing, carbon dioxide toxicity and anxiety; 3) core and inhalation/exhalation temperatures, which indicate the diver's thermal balance" be monitored.

To a degree, but only to a degree, the participants in the present Workshop have ratified the suggestions in the National Plan. They have gone further and demonstrated an important point: the usefulness of

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*A. Galerne, K. Ackles, C. Duff, D. Hall, L. S. Linderoth, Jr. and M. Spencer. 1976. Monitoring Techniques, in National Plan for the Safety and Health of Divers in Their Quest for Subsea Energy. M. W. Beckett, Ed. Undersea Medical Society.

virtually all the parameters that have been discussed depends on future improvement of recording techniques and/or interpretation of their physiological meaning, their processing for meaningful presentation, and better education of dive crews. Furthermore, we have recognized that our standards of interpretation may vary depending on whether we monitor to diagnose impending malfunction in the diver, to control and pace him for maximal work efficiency, or to have a record should things go wrong. We have also been exposed to ideas for alternatives to monitoring for the purpose of real-time interpretation. The suggestion has been made that large amounts of material of carefully monitored dives under well-defined stress situations (in terms of temperature, nitrogen narcosis, strenuous exertion, low visibility, etc.) should be subjected to statistical analysis. This would make it possible to assess risk factors and performance decrements before divers are sent down.

As for answers to the questions above, this Workshop established that only a few recommendations can be made unreservedly about physiological monitoring that would have a sure impact on the diver's safety and performance today. But there are several important recommendations for steps to take today that will have a beneficial effect on diving safety tomorrow---that is how I have perceived our deliberations. However, the reader should form his own judgment. In order to provide him with an overview I have listed below, in the thesis-antithesis form where applicable, a number of major points that we agreed or disagreed on.

<u>Monitoring vital signs in the diver is desirable:</u>

-to indicate whether the diver is alive or not
-to provide clues as to what happened if he died
-to provide experience of what happens to fundamental physiological functions under real in-sea diving conditions so that we have a basis for comparison with data obtained under controlled laboratory conditions
-to alert the diving supervisor to take action to prevent a potentially dangerous situation from deteriorating further
-to give the diver to whom the information should be fed back a chance to make an educated evaluation of his own situation
-because it is the only way to tell when something is wrong with the diver (as opposed to equipment or other external factors)

<u>is unnecessary:</u>

-if his equipment is monitored. The diver's vital signs only show deterioration because something goes wrong physically in the dive, which can be prevented by proper dive planning, improved seamanship, etc.

is meaningless:

-until we have a solid background in laboratory experiments so we know what to expect from the "vital signs" during hypothermia, overstrenuous exercise at depth, etc.
-until the diving supervisors have been sufficiently trained in the physiological and medical interpretation of data

* * * * *

An anticipated difficulty in monitoring in-sea divers is the unwillingness on the part of divers and tenders to cooperate.

The responsibility for obtaining cooperation from dive crews in diver monitoring lies primarily with the diving physiologists and physicians who must do a better job of selling.

Diving supervisors must be better educated in the interpretation of monitored parameters (including sound and vision).

High level officials in the North Sea area have considered regulations prescribing compulsory monitoring of the diver's breathing.

Some of the most puzzling deaths in commercial diving have been among air breathing divers in relatively shallow water.

Commercial diving firms have expressed an interest to participants in this Workshop in collaborating with researchers who want to do physiological monitoring during in-sea dives.

* * * * *

Heart rate:

-is valuable as an indicator of physical stress or metabolic activity.
-is useful to make sure that the diver does not over-exert himself. He should not be allowed to exercise at a rate above 160 per min.

Fixed cut-off points for heart rate should not be set because individual response to underwater exertion is too varied.

Heart rate information is only useful as qualitative information--a warning signal if it becomes very high or low.

Heart rate would become more useful if recorded and interpreted in conjunction with other parameters.

* * * * *

Respiration

-tells how much the diver is exerting himself.
-is a poor indicator of ventilatory effort. Minute ventilation is considerably better and the best indirect measure of the diver's metabolic activity.

Respiratory frequency is easy to monitor via sound or temperature recording at mouth.

A high minute ventilation appears to correlate much better with dyspnea in divers than end-tidal CO_2 levels.

Minute ventilation cannot at present be easily obtained under in-sea conditions.

A new magnetometer method for monitoring minute ventilation shows excellent accuracy and may be available for in-sea use in a couple of years.

* * * * *

Thermal monitoring

Thermal balance of the diver is best monitored by recording heat flow.

Heat flow recording under in-sea conditions will presumably soon be feasible using heat flow discs.

Core temperature is second best (to heat flow recording) but requires a time profile to be of predictive value (should be monitored as ear temperature or with radio pill).

Diver self-evaluation of his own thermal situation may be unreliable.

* * * * *

Eye movement monitoring

Recording of changes in the velocity of eye movements may in a few years become useful in assessing a diver's state of arousal and in making predictions about his ability to perform complicated tasks.

Recording eye movements appears too complicated technically to be useful under in-sea conditions.

* * * * *

Performance measuring

Performance prognostication (for the specific dive) from generalized or individualized information on how various stressors tend to reduce diver performance appears to be a useful approach.

To sharpen the accuracy of performance prognostication requires systematic sampling and statistical treatment of large numbers of observations.

* * * * *

Voice monitoring

Speech monitoring for stress analysis in divers does not look promising.

Voice monitoring is of the highest priority.

Voice monitoring will only reach its full usefulness if diver and tender are trained to speak. Especially, the tender must be trained to ask the proper questions.

The frequency of spoken contacts should at least satisfy some minimum.

Speech intelligibility can be considerably enhanced by selection of proper microphones.

* * * * *

General Comments

Visual monitoring is of great value but requires training for proper interpretation.

* * * * *

Monitoring techniques still suffer from lack of adequate sensors.

The major difficulty is not in hardware but in interpreting what is monitored--much more laboratory work is required before we can make use of what can be picked up from the diver.

Monitoring physiological parameters will become more useful if data are recorded and presented against time so as to show trends of change.

Physiological variables obtained during in-sea conditions should be referenced against the individual physiological profile of the diver obtained earlier under defined stress conditions. This "profile" should be stored on memory chips to be used in computer during "in-sea" dives.

Redundancy in physiological monitoring is desirable.

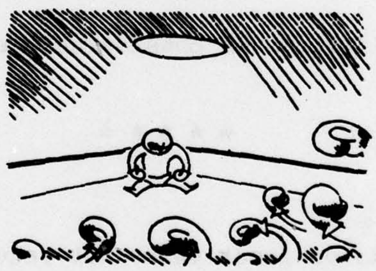
Given the proper software, present computer and microprocessor techniques can present the data in real time, in a form the diving supervisor can easily understand and work with.

Recording of data, including voice, should be stored for legal purposes to allow retrospective analysis of accidents, and to accumulate experience of what distinguishes uneventful dives from dives in which the diver had problems.

* * * * *

Diver and tender should be trained together so that they know each other's behavior and reactions.

Formal training of divers and tenders should include exposure to adverse conditions such as hypothermia and exertion dyspnea to provide them with a common frame of reference.



PROBLEMS

Problems worthy
of attack
prove their worth
by hitting back.

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1. REPORT NUMBER WS: 78-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Monitoring Vital Signs in the Diver		5. TYPE OF REPORT & PERIOD COVERED Special Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Claes E.G. Lundgren, M.D., Ph.D.		8. CONTRACT OR GRANT NUMBER(s) N00014-74-C-0319
9. PERFORMING ORGANIZATION NAME AND ADDRESS UNDERSEA MEDICAL SOCIETY, INC. 9650 Rockville Pike Bethesda, Maryland 20014		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE March 17-18, 1978
		13. NUMBER OF PAGES 112
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Diver - Monitoring - Performance - Physiological Monitoring - Pulmonary Temperature

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The workshop considered all aspects of monitoring vital signs in the diver. It was concluded that monitoring was highly desirable and was within the capability of present equipment. It was recognized that monitoring in-sea divers is difficult and complicated because of unwillingness on the part of divers and tenders to cooperate. Special consideration was given to monitoring heat loss, respiration, temperature, eye movement. Performance

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measures were considered important and voice monitoring was considered of the highest priority.